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**THESIS**

**ROLL STABILIZATION FOR  
T-AGOS CLASS SHIPS**

by

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March, 1997

Thesis Advisor:

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**ROLL STABILIZATION FOR T-AGOS CLASS SHIPS**

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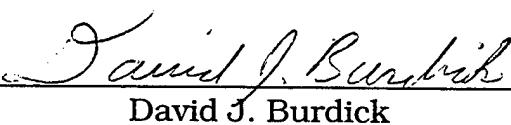
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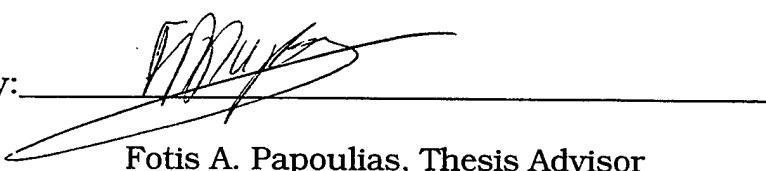
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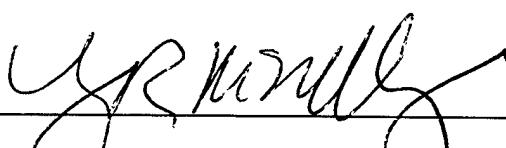
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## **ABSTRACT**

The T-AGOS class 3 and 4 ships are under consideration by the United States Air Force for use as sea-based radar platforms. In order to meet mission requirements, their roll motion must be reduced. Several roll damping methods appropriate for this class of ships are considered. Bilge keel stabilization is studied in more detail and various sized bilge keels are analyzed, utilizing a seakeeping prediction program, for the full range of ship speed and sea states. Operability indices at several roll angles and for various bilge keel shapes are developed and compared. Design considerations based on the above studies are made.



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## **I. INTRODUCTION**

### **A. OVERVIEW**

Ships can be initially designed for a variety of purposes or uses. But, as the times change, they may be no longer needed for this original use or may be considered for other types of operations which could require it to operate in a different environment than originally intended and designed for. The operating characteristics, in this new environment, may not be suitable for the intended use of the ship.

The United States Air Force has been considering the use of T-AGOS class 3 and 4 ships as sea-based radar platforms. These ships were originally designed for surveillance and ASW operations. The operating characteristics for the original mission, and thus what the ship was designed for, are different to what would be required for this current consideration. To act as a sea-based radar platform, consideration would have to be given to improving the seakeeping qualities of the ship, in particular with regards to roll motion. Various methods exist for improving the roll of ships and are discussed in the next section.

In this study, the effects of bilge keels on the ship were examined. In particular, various sizes of bilge keels for the full range of ship speed and sea states. A FORTRAN program, SHIPMO [Ref. 1], was utilized to

perform the roll angle calculations for the varying conditions. The data obtained was utilized, in the form of various graphs and polar plots, to show the effects of bilge keels. Operability indices were found for each of the bilge keels under examination. If properly compared, these operability indices can provide a useful comparison of the effectiveness of bilge keels.

## **B. STABILIZING METHODS**

Several methods exist for improving the seagoing stability of the ship and include, but not limited to, fin stabilizers, roll tanks, and bilge keels and may be used together or individually. The stability characteristics of the ship and the effects of employing these various methods can easily be seen by looking at the roll characteristics that are experienced by the ship. Various advantages and disadvantages exist for each of these methods and must be considered when determining a particular method to be used. [Ref. 2]

The first type of stabilization technique that is available are active fin stabilizers. These produce a controlled roll moment where the phase and amplitude is such that it counteracts the external heel moment. The fins are most effective at higher speeds, generally greater than ten knots, since the force on the fin varies directly proportional to the speed of the

ship. Below ten knots, the stabilizing moment available is not adequate to effectively counter the heel moment. In addition, the load on the fin or fin pivot may be such that the fin is unable to undergo full angular displacement at certain speeds. This could result in degraded performance at other additional speeds. Various parameters such as shapes, ship locations, and angles of attack can be varied to help obtain the maximum performance from them. The following are advantages and disadvantages of active fin stabilizers:

**Advantages:**

1. They offer the highest possible roll reduction with no reduction in static stability characteristics. They are the most effective of all single stabilizing devices.
2. They are used in ships of different sizes.
3. They inflict very small increases in ship resistance and have small auxiliary power requirements.

**Disadvantages:**

1. They are not effective at low speeds.

2. They take up moderate machinery space, especially if they are retractable. This is desirable as they are less prone to damage.

3. High initial cost due to the controlling equipment and machinery required.

The next method of stabilization that exists are roll tanks. These tanks can be active or passive stabilizers which uses ship's motion in such a way to cause water in the tanks to move in a direction as to oppose the ship's motion. Two different tank configurations can be employed - free surface or U-tube. A major limitation to this method is that the tanks can only be tuned to one frequency. This is usually the natural frequency since this is most likely where the largest roll angles will occur. They are not as effective at other frequencies and can actually increase the roll angles attained at these other frequencies. More sophisticated methods exist where the resistance in the duct can be adjusted for the frequency of the exciting waves which allows dampening to be achieved for all frequencies. The advantages and disadvantages for this method of roll stabilization are as follows:

Advantages:

1. High roll reduction rates of up to 70% are possible.

2. They remain effective at low speeds.
3. Vary little auxiliary power is required.
4. Moderate initial cost and low maintenance required.
5. Not vulnerable to damage since they are internal to the hull.

Disadvantages:

1. Moderate space is required in the hull.
2. 1-4% reduction in deadweight capacity for constant displacement.
3. Reduction in initial static stability due to free surface effects, especially for free surface tanks.

The final method of stabilization that was considered was bilge keels. Bilge keels are the most widely used and simplest kind of roll stabilization in current use. They consist of a fin fixed to the hull at or near the bilge. The natural period of the roll of the ship is proportional to the radius of gyration of the ship. By attaching this fin, the radius of gyration of the ship is effectively increased. This results in an increased mass of water to roll with the ship and therefore an increase in the

period of the roll. Under forced rolling conditions, such as in a seaway, the increased natural period that results from the bilge keel results in a roll amplitude reduction. The increased resistance to roll due to viscous-eddy effects supplied by the bilge keels plays an even larger role in roll reduction. Energy is dissipated by viscous flow from around the ship and this energy dissipation is increased substantially by bilge keel use. The advantages and disadvantages of this method are as follows:

Advantages:

1. Bilge keels are simple and easy to fit.
2. They remain effective at relatively low speeds.
3. Negligible reduction in ship's deadweight capacity, no reduction in initial static stability, no auxiliary power requirements, and negligible space occupied by the hull.
4. Low initial cost.

Disadvantages:

1. Since they are external to the hull, there is added resistance to ahead motion that must be overcome by the main engines.

2. Comparatively to other methods, bilge keels offer smaller amounts of roll reduction.
3. Bilge keels, carefully aligned to flow around the hull in calm waters to reduce forward motion resistance, can lead to added resistance during roll motion.
4. Vulnerable to damage.

All advantages and disadvantages of the various methods must be considered when determining which stabilization method is best suited for the application of interest. Some particular advantages or disadvantages may be of greater importance in the decision process than others. Active fin stabilizers, although the most effective, suffer from severe degradation at low speeds. Passive roll tanks have comparatively large response times and quick changes in roll motion can disrupt the operation of the roll tanks. Active roll tanks require large initial costs and auxiliary power with minimal added advantage. Due to the simplicity and relative effectiveness at low speeds, bilge keels were the method of choice.



## II. EVALUATION OF RESPONSE

### A. REGULAR WAVE MOTION

An important consideration for any floating body is the effects of waves on the free surface, especially surface waves with a period of a few seconds. Other waves, such as subsurface waves, usually have much longer periods and have negligible effect compared to surface waves.

When analyzing these types of waves, some assumptions must be made. These include that the fluid is ideal and body motions are sufficiently small to linearize. From this, the appropriate fluid mechanics tools can be utilized to describe sea waves and ship motions based on potential flow theory. [Ref. 3]

Potential, or ideal, flow theory is based on a couple of assumptions. The first assumption is that mass is preserved. If a control volume is placed around the object of interest and the fluid around it, then the mass which enters the volume must either accumulate in the control volume or leave. Utilizing the divergence theorem, conservation of mass, and assuming that density remains constant, the final form of the continuity equation inside the control volume becomes:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

The next assumption is that flow is irrotational. This results in the property that circulation around any closed curve is zero or:

$$\int_c \vec{U} \cdot d\vec{r} = 0 \quad (2)$$

From equation (2) and the definition of a velocity potential, the continuity equation can be written as:

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (3)$$

which is better known as Laplace's Equation.

Once the velocities and  $\phi$  have been solved for and assuming unsteady, irrotational flows, pressure can be found with the help of Bernoulli's equation and can be computed from:

$$p = -\rho \frac{\partial \phi}{\partial t} - \frac{1}{2} \rho \nabla \phi \cdot \nabla \phi - \rho g z \quad (4)$$

The plane progressive wave system is the simplest free surface wave formation scheme. It is two dimensional, sinusoidal in time, and propagates with a phase velocity such that an observer moving with the same velocity will make the wave appear stationary. Adopting a Cartesian coordinate system, the free surface elevation can be expressed in the following form:

$$\eta(x, t) = A \cos(kx - \omega t) \quad (5)$$

where: A-wave amplitude

k-wave number

Ship motions induced by regular wave motion are of most concern. In the simplest case, the waves incident upon the body may be assumed as plane progressive waves of small amplitude and sinusoidal time dependence. Ship motion is also assumed sufficiently small for linear theory to hold. Waves incident to a stationary or moving body will cause the body to move with six degrees of freedom or to heave, pitch, roll, yaw, surge, and sway. In general, the body motion in any of the six degrees of freedom can be expressed as:

$$\eta_j = A \sum_{j=1}^6 [D_{ij}]^{-1} F_i \quad (6)$$

where: A-wave amplitude

F-exciting force per unit wave amplitude

D-matrix of equations of motion

A new fundamental quantity can also be introduced, known as the Response Amplitude Operator (RAO), as follows:

$$Z_j(\omega, U, \theta) = \frac{\eta_j}{A} \quad (7)$$

This corresponds to the complex amplitude of body motion in the jth mode in response to an incident wave of unit amplitude, frequency, and direction, and is generally known as the transfer function, which can be calculated once the added mass, damping, exciting, and hydrostatic forces are known.

The responses derived from the above motions are important for evaluating the seakeeping performance of the ship. Computation of the RAO's is simple once the added mass and damping coefficients are known. But, this is the most difficult part. A technique for determining these values utilizes the Strip theory. In this method, the ship is assumed as a slender body. In other words, the beam and draft are much smaller than the length of the ship. The cross-section of the ship are divided into "strips", or as for Frank's method [Ref 4]- a series of straight line segments integrated along the entire length of the ship so as to determine the overall effect. By utilizing the strip theory method, the ship's motions in regular waves can be determined. Through a combination of the above equations, the resulting linearized simultaneous equations that must be solved for to determine these motions are:

$$\sum_{k=1}^6 \left\{ -\omega_e^2 (M_{jk} + A_{jk}) + i\omega_e B_{jk} + C_{jk} \right\} \zeta_k = F_j^I + F_j^D \quad j=1..6 \quad (8)$$

where: M - mass matrix

A-added mass matrix

B-dampening matrix

C-hydrostatic restoring force matrix

$F^I$  -Froude Krylov exciting force in the jth mode of motion

$F^D$  -Diffraction exciting force in the jth mode of motion

$\zeta_k$  -complex amplitude of motion in the kth direction

## B. ROLL DAMPING

Roll damping can be accomplished by a variety of methods as discussed above. The roll damping hydrodynamic moment used in equations of motion tends to be nonlinear in nature with respect to the roll angle. To allow roll damping to be calculated, as in SHIPMO [Ref 5], it must first be linearized. Utilizing the method described by Himeno (1981) [Ref 6], the roll damping coefficient can be assumed in regular waves as:

$$B_{44}(\zeta_4) = B_1 + \frac{8}{3\pi} \omega_e \zeta_4 B_2 \quad (9)$$

where: B - damping matrix/coefficients

$\zeta$  - Complex amplitude of motion

$\omega$  - wave frequency

The damping coefficients are a function of frequency, the point about which roll occurs, and the forward speed. In regular wave motion with constant forward speed, the damping coefficient values are constant about a fixed point. When irregular or random waves are encountered, the following equation by Himeno applies:

$$B_{44}(\zeta_4) = B_1 + \sqrt{\frac{8}{\pi} \sigma B_2} \quad (10)$$

where:  $\sigma$  - variance in angular roll velocity

The damping coefficients are composed of the following components:

$$\begin{aligned} B_1 &= B_F + B_W + B_L \\ B_2 &= B_E + B_{BK} \end{aligned} \quad (11)$$

where:

$B_F$  - frictional damping component

$B_W$  - wave generation damping component

$B_L$  - hull lift damping component

$B_E$  - hull eddy damping component

$B_{BK}$  - bilge keel damping component

The above components are based mainly on experimental analysis which are measured about a fixed point (roll center) and are usually limited in their range of applicability. If the beam to draft ratios are much more than about 2.5, the eddy dampening by Himeno tends to overpredict the eddy component. In addition, determining the point about which the ship is rolling, or roll center, can prove to be difficult. In particular, a ship in a seaway has only an instantaneous roll center and can be calculated as follows:

$$RC = \left( \frac{|\zeta_2|}{|\zeta_4|} \right) \{ \cos(\alpha_2 - \alpha_4) - \tan(\omega_e t + \alpha_4) \sin(\alpha_2 - \alpha_4) \} \quad (12)$$

where:  $\alpha_2$  - sway phase angle

$\alpha_4$  - roll phase angle

### C. MOTIONS IN A SEAWAY

Wave patterns in an open sea are ever changing with respect to time and space, in a manner that appears to defy analysis whether it is linear or second order Stokes. [Ref 7] Ambient waves on the surface of the sea are dispersive as well as random in nature where random refers to the character of the wave height distribution. The distribution of sinusoidal waves are such that they have continuously distributed amplitudes and phases such that the summation of the variation of wave height with time is not systematic in any respect, but random. The generating mechanism is, predominantly, the effect of wind in the atmosphere upon the water surface. Spectral Density,  $S(\omega)$ , provides useful data that has been removed from a random wave record,  $h(t)$ . The random wave record can be processed such that a  $S(\omega)$  vs. wave frequency,  $\omega$ , curve can be generated. The spectral density is obtained from a wave height record taken during a period of time when sea conditions are considered unchanging (stationary) for a certain sea state. The spectral energy density,  $S(\omega, \theta)$ , (or directional energy spectrum) can be integrated over all wave directions,  $\theta$ , to give the frequency spectrum as given below:

$$S(\omega) = \int_0^{2\pi} S(\omega, \theta) d\theta \quad (13)$$

For open seas, it is appropriate to assume that waves are unidirectional which allows the energy spectrum to be proportional to a delta function in  $\theta$  where the wave crests can be considered parallel and the fluid motion to be two dimensional. Wave spectra of this form is considered long crested and is sufficient to describe the wave environment.

In naval architecture and ocean engineering, it is usually appropriate to assume waves to be long crested. With this simplification, existing information for the energy spectrum, based on theory and full scale observations, can be used for the energy spectrum. Usually, we are more concerned with larger waves. The most common parameter that takes this into account is the significant wave height,  $H_{1/3}$ , which is defined as the average of the highest one third of all waves and can be expressed as follows:

$$H_{1/3} = 4.0(m_o)^{1/2} \quad (14)$$

Where  $m_o$  is the integral of  $S(\omega)$  over all frequencies. More generally, the moments,  $m_i$ , of the spectrum can defined by:

$$m_i = \int_0^{\infty} \omega^i S(\omega) d\omega, i = 0, 1, 2, \dots \quad (15)$$

Also, the average frequency of the spectrum, defined as the expected number of zero upcrossings of the body that is considered per unit time (i.e. the number of times the

wave amplitude passes through zero with a positive slope), can be determined as follows:

$$\omega_z = \left( \frac{m_2}{m_o} \right)^{1/2} \quad (16)$$

The average period between zero upcrossings is:

$$T_c = \frac{2\pi}{\omega_c} = 2\pi \sqrt{\frac{m_o}{m_2}} \quad (17)$$

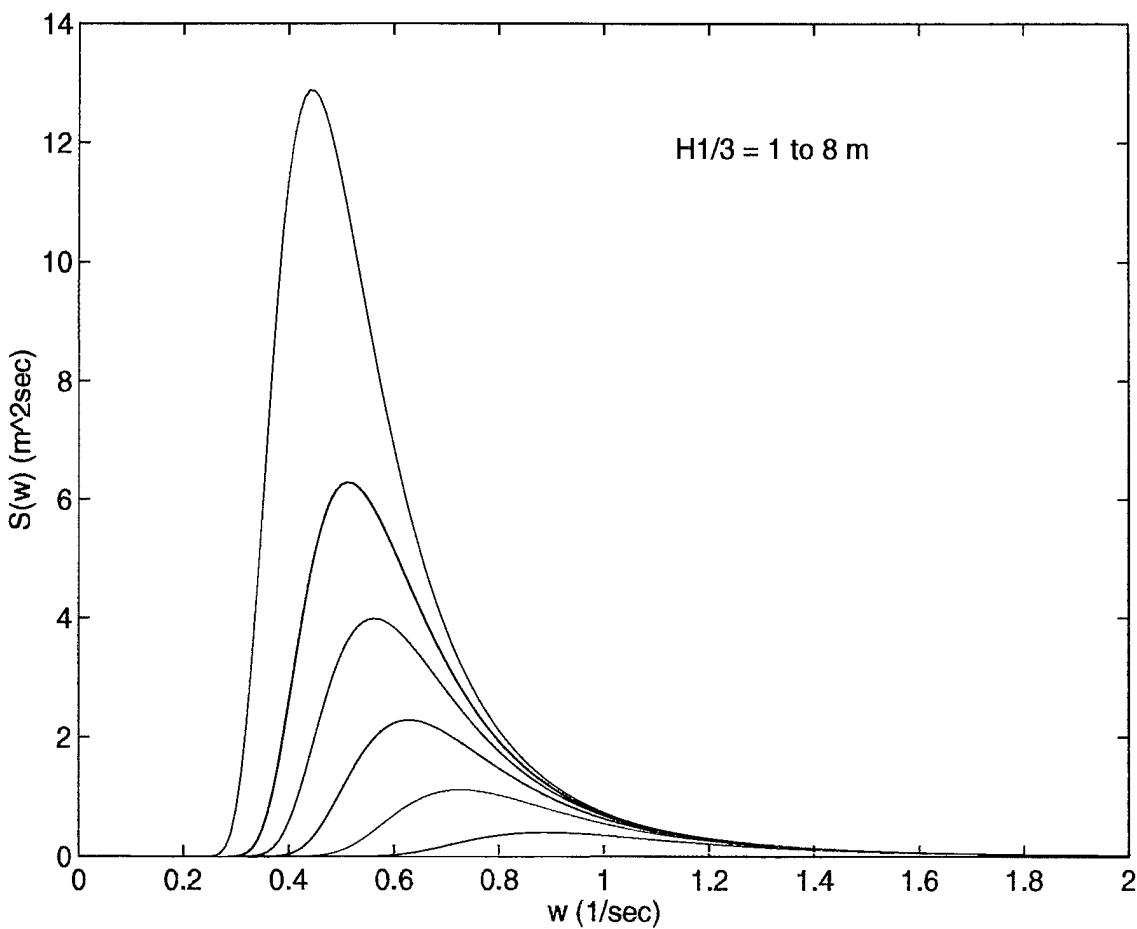


Figure 1. Typical Pierson-Moskowitz wave spectrum

A good model for fully developed seas is the Pierson-Moskowitz spectrum. Figure 1 shows a typical Pierson-Moskowitz spectrum. This spectrum is based on significant wave height where it is assumed that the wave spectra has reached a steady-state equilibrium and is independent of duration and fetch. In other words, the waves are considered fully developed. It is recognized as an asymptotic form reached only after an extended period of wind with no contamination from an underlying swell and can be given as follows:

$$S(\omega) = 0.0081g^2 / \omega^5 \exp\left(-0.032\left(g / H_s \omega^2\right)^2\right) \quad (18)$$

where:  $g$  - acceleration of gravity

$H_s$  - significant wave height

$\omega$  - wave frequency

Once the frequency spectrum is found, another quantity can be determined which will allow the spectral description of waves to be generalized into regular harmonic waves. As previously discussed, the Response Amplitude Operator, RAO, is a nondimensional quantity that can be used to relate the amount of heave amplitude per unit wave length. If the sea waves are described by a random distribution and if body response to each wave is defined by a RAO, the body response will be:

$$\eta_j(t) = \Re \iint Z_j(\omega, \theta) e^{i\omega t} dA(\omega, \theta) \quad (19)$$

where:

$\Re$  - any body response

$Z$  - response amplitude operator

$\omega$  - wave frequency

$\theta$  - wave direction

The body response is also a random variable. The seaway spectrum may be related to any body response by the following equation:

$$S_R(\omega) = |Z_R(\omega)|^2 S(\omega) \quad (20)$$

where:

$S(\omega)$  - spectrum of the seaway

The above RAO is not only valid for regular wave motions but also in a spectrum of random waves. This allows for the assumption that a vessel with favorable characteristics in regular waves will also have the same favorable characteristics in irregular waves. From equation 20, various ship's motions can be calculated from a given sea spectrum, such as the Pierson-Moskowitz discussed previously.

## **D. CALCULATION PROGRAM**

The computer program SHIPMO [Ref 1] was utilized to make the various calculations, more specifically roll calculations, needed for this study. The computer program calculates a variety of motion responses and is able to predict ship motions in six degrees of freedom. Regular wave motions are calculated utilizing a modified strip theory of Salvesen, Tuck, and Faltinsen (1970) [Ref 8] which is based on a slender body in an ideal fluid with corrections made for viscous and other effects. Two dimensional properties are calculated using Frank's method (1967) [Ref 9] with a lid applied to remove any irregular frequencies which can cause calculation difficulties if not applied. Frank's method is computationally fast and any ship's cross-section can be approximated with as much accuracy as desired. The wave spectrum can either be user inputted or chosen from one of six methods available in the program. All calculations, for this study, were based on the classical Pierson-Moskowitz spectrum as described in the previous section.

The program reads in the initial ship data and calculates the potential for the four modes of motion - pitch, roll, yaw, and sway, over the specified frequency range at each designated cross section utilizing Frank's method. The calculations are based at the ships' amidships centerline position unless otherwise specified. The program allows for a maximum of 21 stations to be selected along the length of the ship, with

a maximum of 15 input points for each station. These are required to provide the hull shape data necessary for the various calculations. The wave spectral ordinates are calculated by the Pierson-Moskowitz method as discussed above. The spectral ordinates are also used to determine the response amplitude operator as was also previously discussed. The motion amplitude is calculated in all six degrees of freedom with the horizontal and vertical plane motions solved separately. Roll dampening is calculated by the Himeno method with eddy dampening for box barges with sharp corners being calculated by either Ikeda's (1977) [Ref 10] or Yamashita and Katagiri's method (1980). [Ref 11] For bilge keel damping, the Himeno method is also utilized. From this, the desired ship's motions can be calculated over ship's speed, heading angle, and wave frequency variations.

The program required a data initialization file, SHIPMO.IN, and is included in Appendix A. The file inputs a variety of constants required for the proper computations to be made. Bilge keel width, depth, and location are inputted from this file. Station positions make up the majority of the file which include the station position relative to the center of the ship. For each station, hull depth and width positions relative to the center and water lines, are provided with the first input point located at the keel of the ship.

## E. SHIP AND ENVIRONMENTAL CONSIDERATIONS

The analysis performed in this study were based on the Class 4 T-AGOS ship.

Table 1 provides some of the general characteristics of the ship that were necessary for the calculations.

Length	224 feet
Location of Centerline	97 feet aft of bow
Design Draft	15 feet
Maximum Ship Speed	11.3 knots

Table 1. General Characteristics T-AGOS Class 4 Ships

SHIPMO, as described in the previous section, was utilized to determine the roll characteristics of the ship based on different bilge keel characteristics. Hull width and depths for various locations along the length of the ship were required for the program's calculations. These were obtained from the body plans for the T-AGOS 4 class ship. [Ref 12] A scaled version of the one actually used may be viewed in Appendix B. The actual data inputted for each of the reference points may be found in the data input file SHIPMO.IN in Appendix A.

Roll calculations were made through the entire speed and sea state spectrum. Speeds of the ship were incremented from zero to 12 knots in two knot speed

increments. Sea states are based on and provide an indicator of the heights of the waves, usually the significant wave height, being encountered by a vessel. They range from 1, relatively calm seas, to 8 which are usually only encountered during strong storms such as hurricanes. Table 2 provides the significant wave height for each of the sea states considered.

Sea State	Significant Wave Height (feet)
1	1.9
2	4.1
3	5.7
4	7.4
5	13.0
6	20.8
7	40.3
8	61.6

Table 2. Sea State vs. Significant Wave Height



### **III. ROLL RESPONSE RESULTS**

#### **A. ROLL CALCULATIONS**

As discussed, SHIPMO was utilized to make the roll calculations necessary for this study and a sample input file is included in Appendix A. The ship's roll characteristics were analyzed based on several bilge keel sizes including no bilge keel. Appendix C provides a sample of the program that was utilized to analyze the data obtained and print out the results. Table 3 lists the different bilge keel sizes that were analyzed. The maximum bilge keel width was based upon two-thirds the length of the ship and subsequently divided in half for each smaller size. A maximum width of three feet was set and reduced in size in one foot increments. Each bilge keel was analyzed such that it was assumed centered along the centerline of the ship.

Length x Width (ft x ft)
150x3
150x2
150x1
75x3
75x2
75x1
37.5x3
37.5x2
37.5x1

Table 3. Summary of bilge keel sizes analyzed

To ensure that a good representative data set was obtained for each bilge keel configuration, enough data points were required. For each ship's speed analyzed, the roll angle was found for each sea state at 22.5 degree increments of wave direction around a 360 degree circle centered on the ship.

Once this data was obtained, a curve of significant roll angles placed on the ship for each sea state and a given speed and bilge keel configuration, could be found utilizing the spline curve fitting function of MATLAB [Ref 13] for each degree of

wave motion from 0 to 360 degrees. Enough data was required to ensure a smooth fit of the curves. To illustrate this point, a graph of the roll angles for no bilge keel and a ship's speed of 2 knots may be seen in Figure 2. Similar graphs for all the other ship's speeds and bilge keel configurations could also be produced if needed.

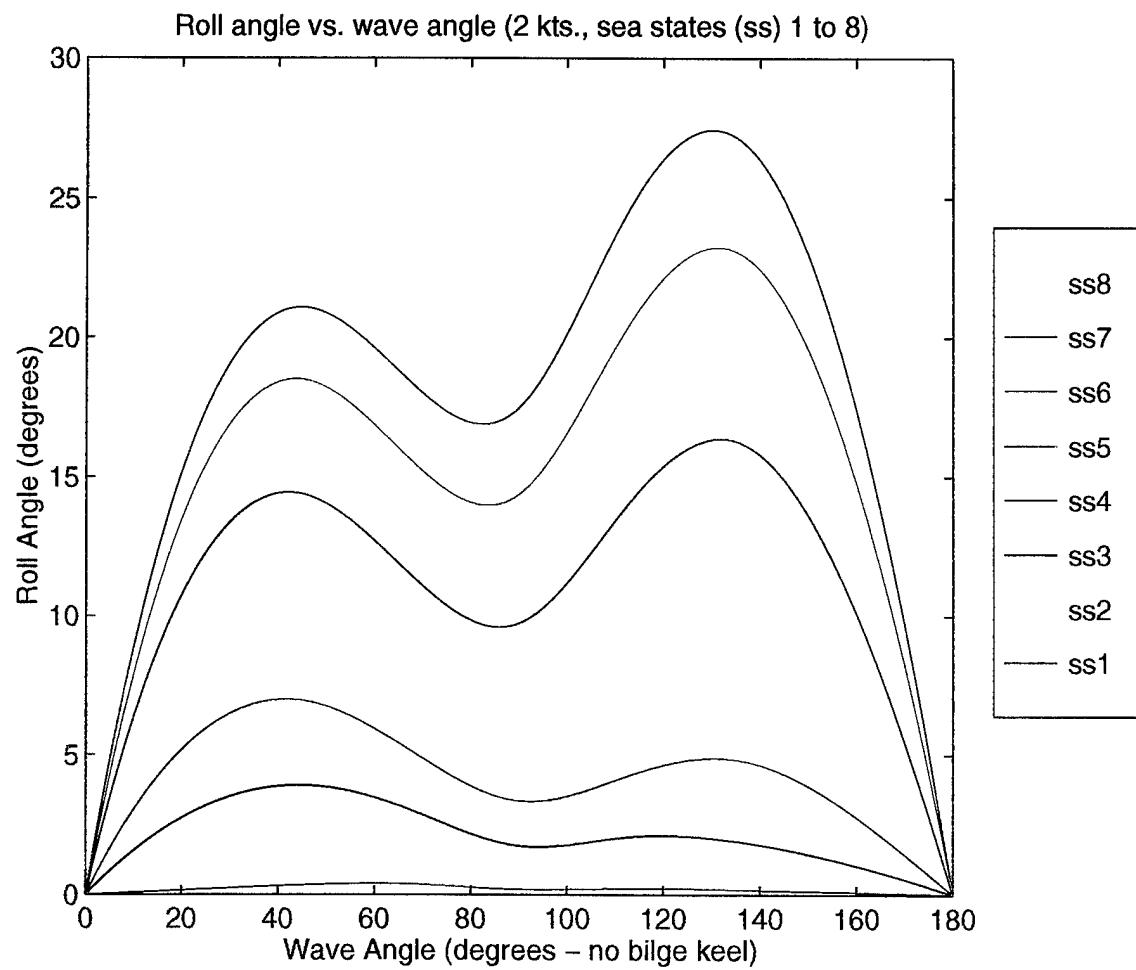


Figure 2. Roll Angle vs. wave angle (no bilge keel and 2 knots ship speed)

From the data obtained as just discussed, a splined curve of roll angles for all sea states for each degree of wave motion was found. From this, the maximum allowed sea states to produce a roll angle of 2, 4, or 6 degrees were found. A polar plot of this data for each bilge keel configuration and respective speeds are shown in figures 3 to 72. In addition, polar plots combining all ship speeds for a certain bilge keel configuration were generated and can be observed in figures 73 to 102. The next section discusses the effectiveness of bilge keels. Operability indices were also determined and plotted to help show this.

By examining the figures, several observations become evident. As was expected, the maximum allowed sea state increased as the maximum allowed roll angle was increased and as ship's speed was increased, the maximum allowed sea state correspondingly decreased. Beam seas seemed to have the least effect on the roll characteristics of the ship and roll was assumed zero for sea directions relating to the bow or stern of the ship. The largest effect on roll angle came from quartering seas with quartering seas aft the beam having the largest effect. Thus, aft quartering seas provided the limiting position for roll angle limits. As can be seen, significant roll reduction can be expected by the use of bilge keels.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

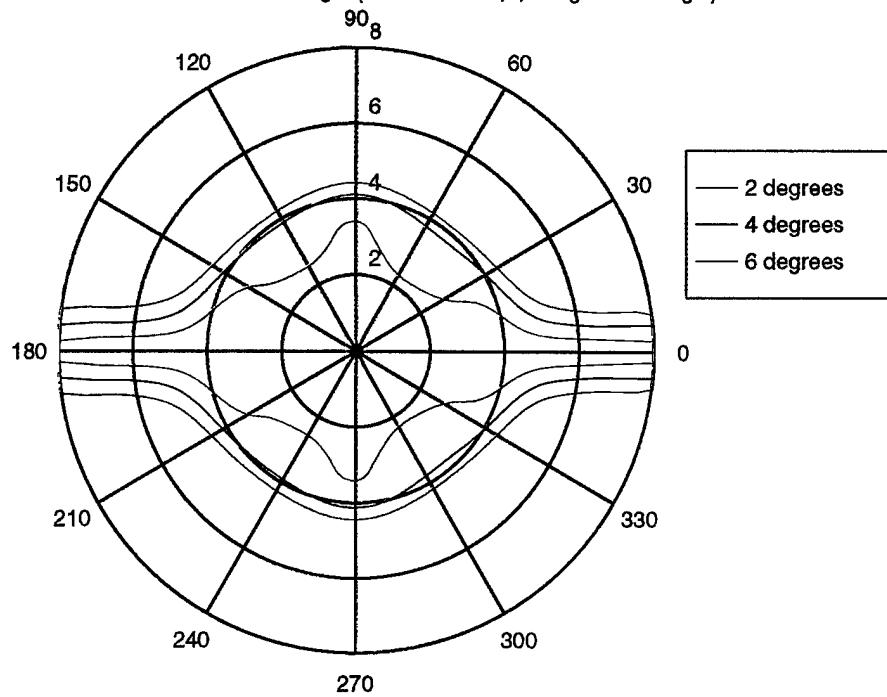


Figure 3. Sea state vs. wave angle for no bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

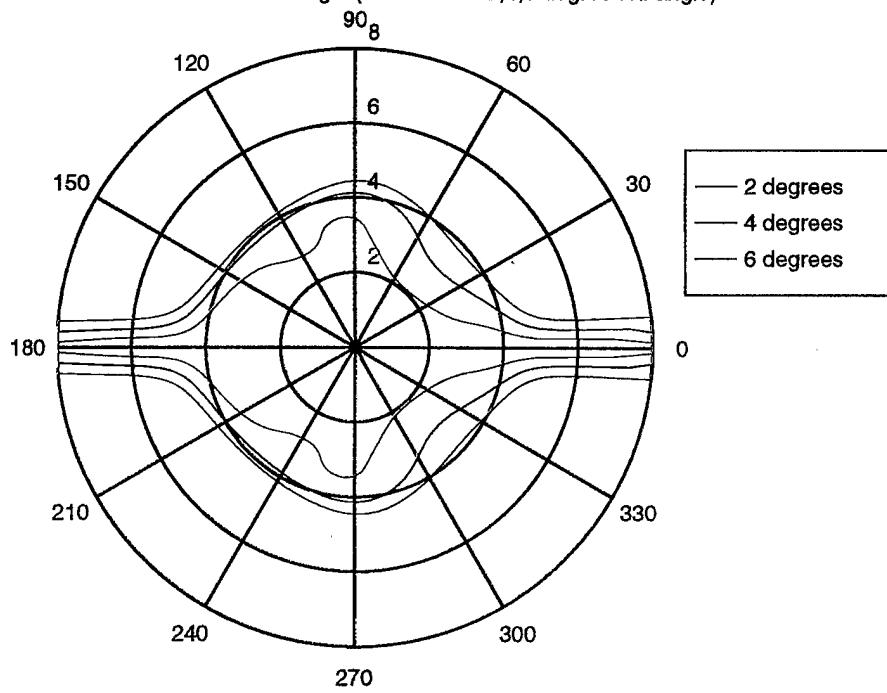


Figure 4. Sea state vs. wave angle for no bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

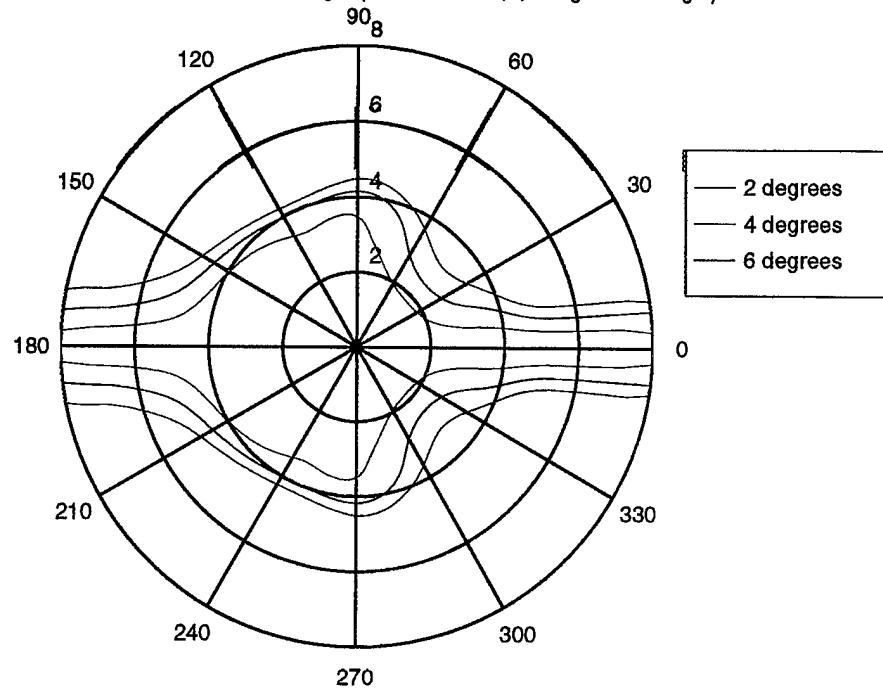


Figure 5. Sea state vs. wave angle for no bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

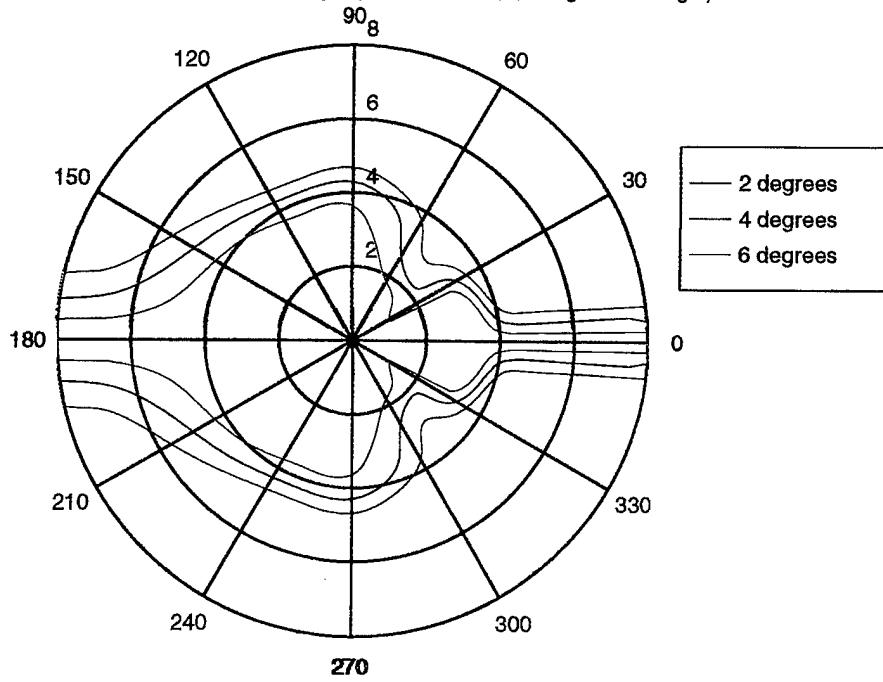


Figure 6. Sea state vs. wave angle for no bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

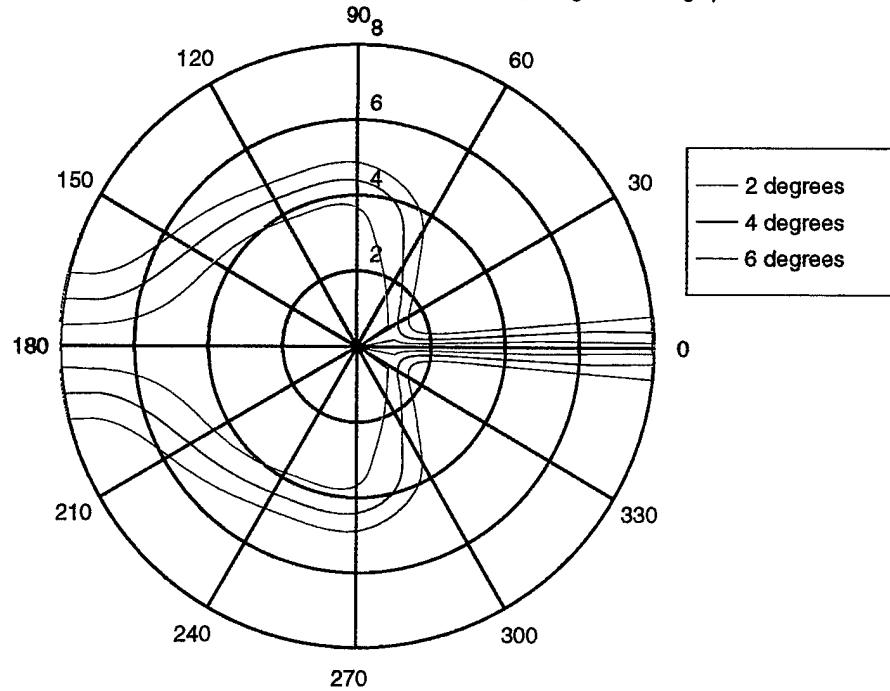


Figure 7. Sea state vs. wave angle for no bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

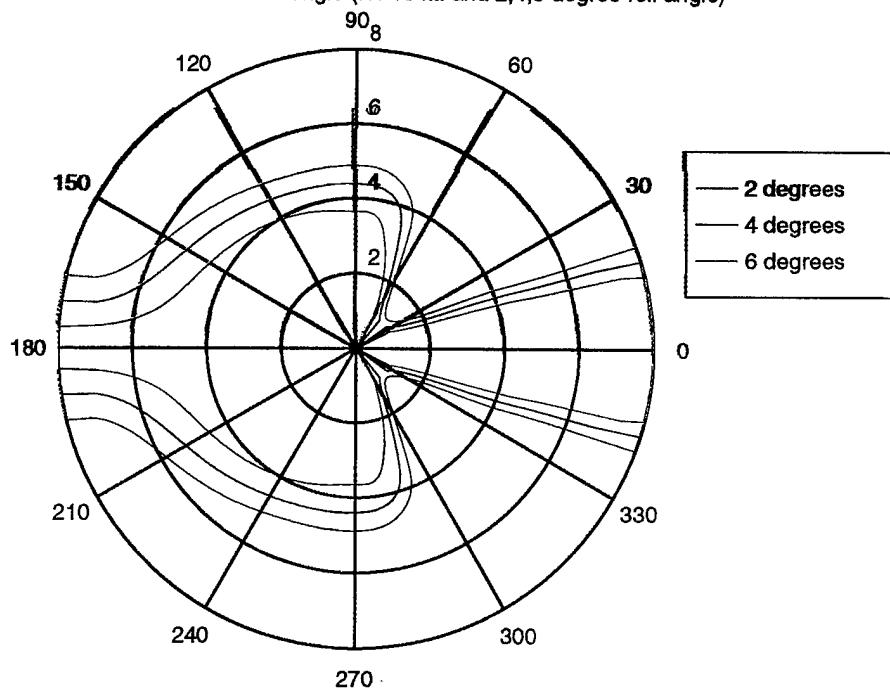


Figure 8. Sea state vs. wave angle for no bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

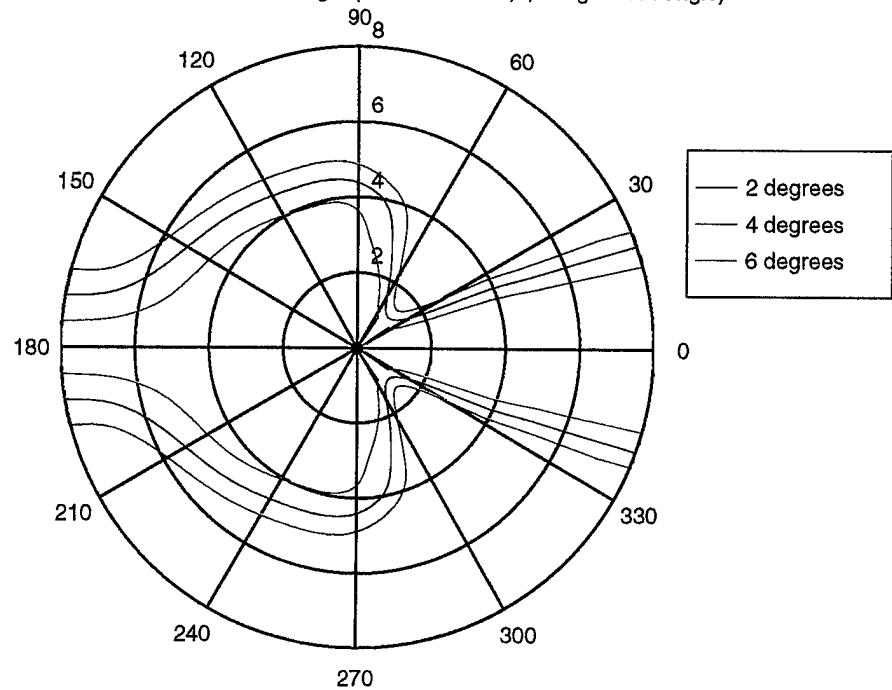


Figure 9. Sea state vs. wave angle for no bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

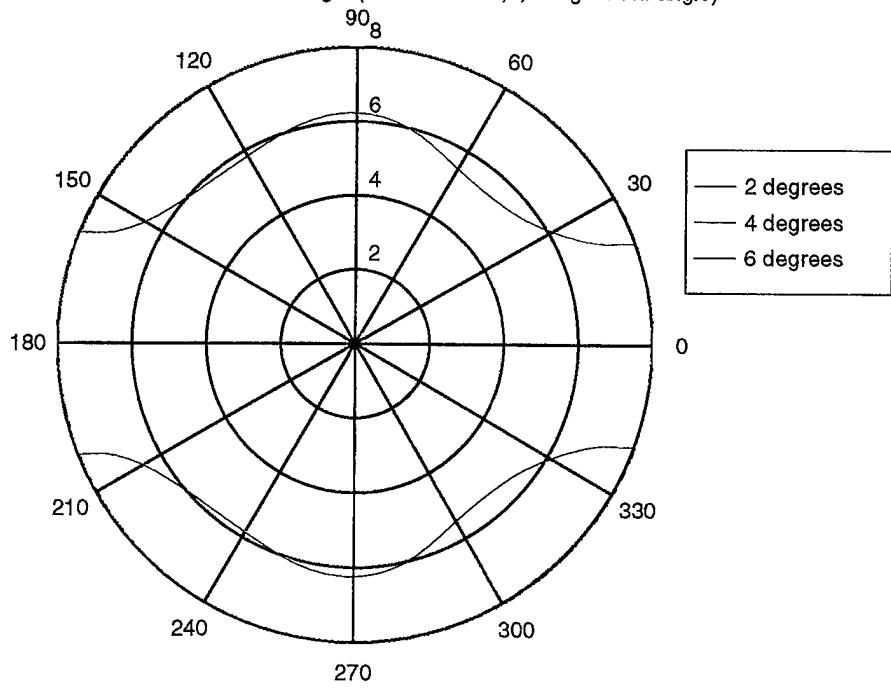


Figure 10. Sea state vs. wave angle for 150x3 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

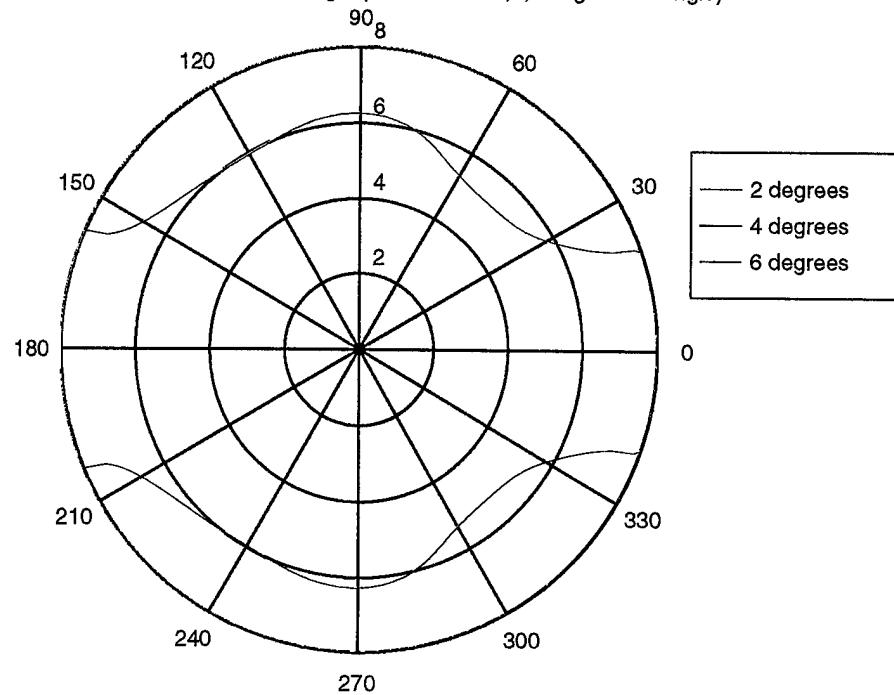


Figure 11. Sea state vs. wave angle for 150x3 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

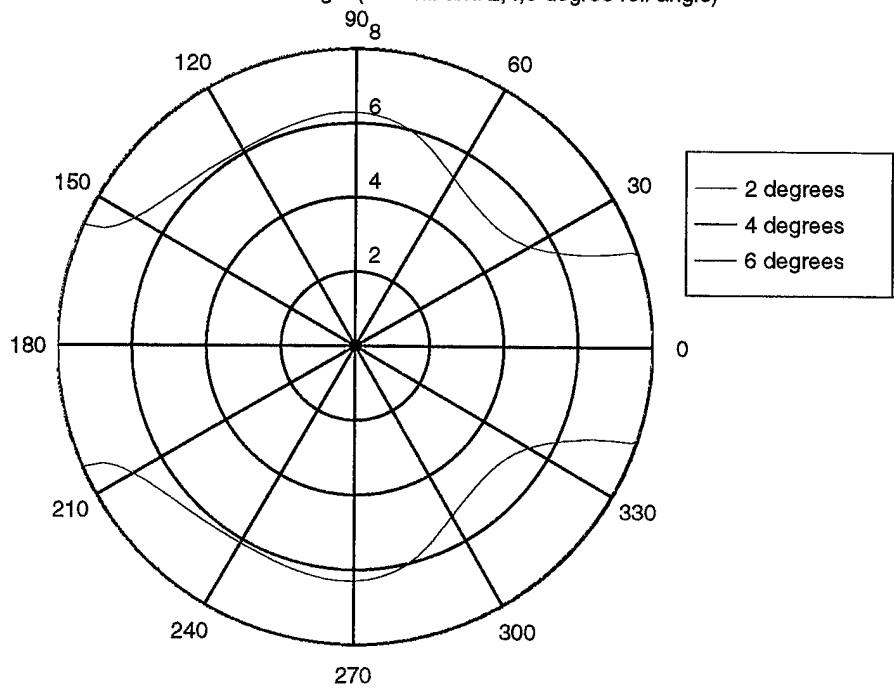


Figure 12. Sea state vs. wave angle for 150x3 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

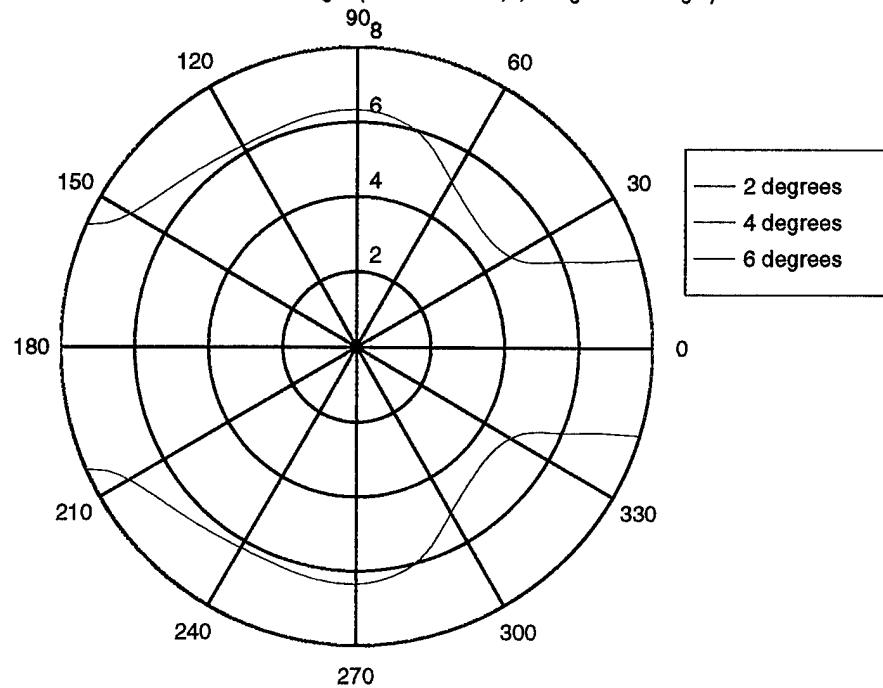


Figure 13. Sea state vs. wave angle for 150x3 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

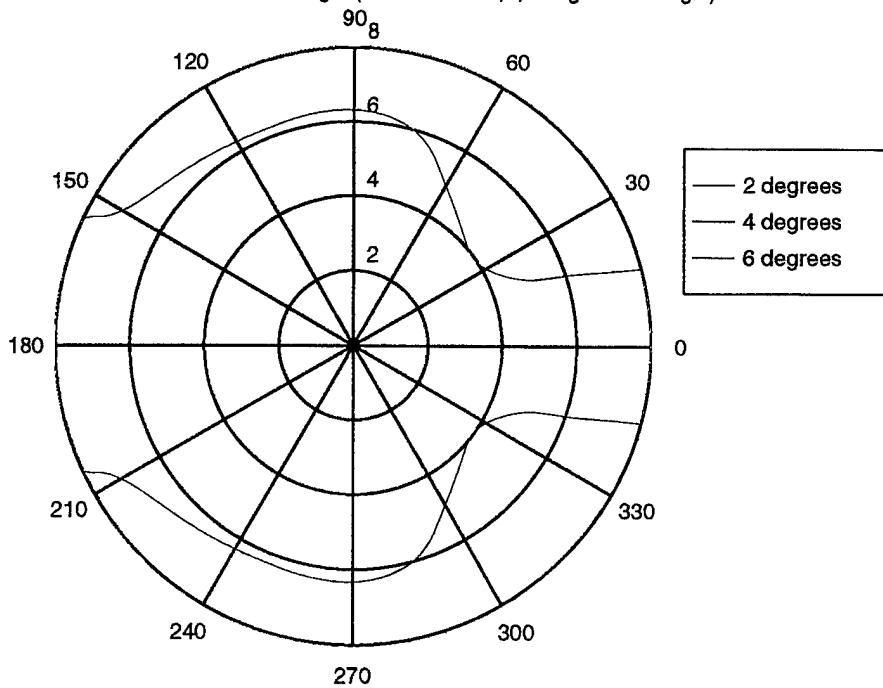


Figure 14. Sea state vs. wave angle for 150x3 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

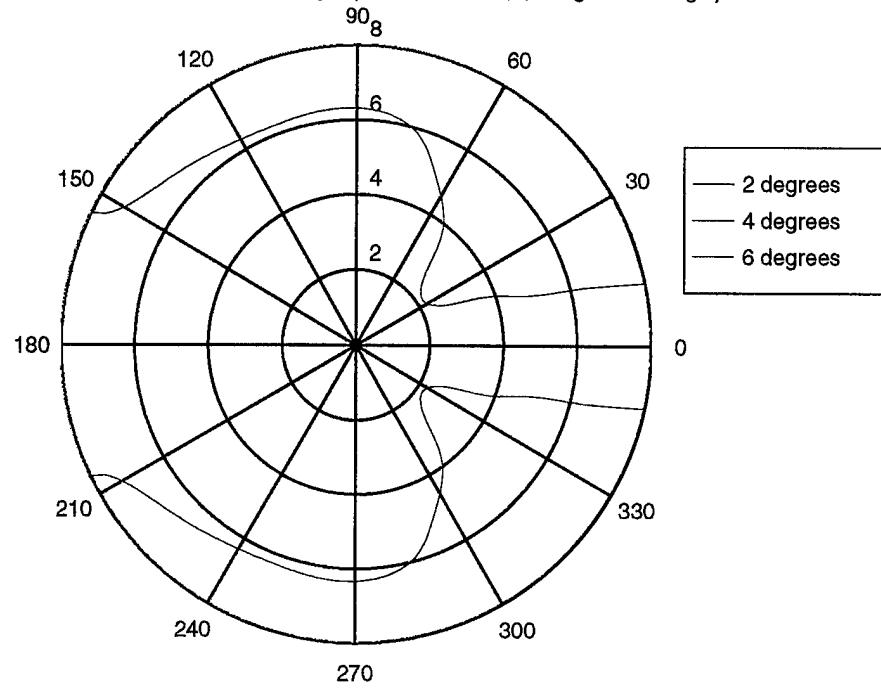


Figure 15. Sea state vs. wave angle for 150x3 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

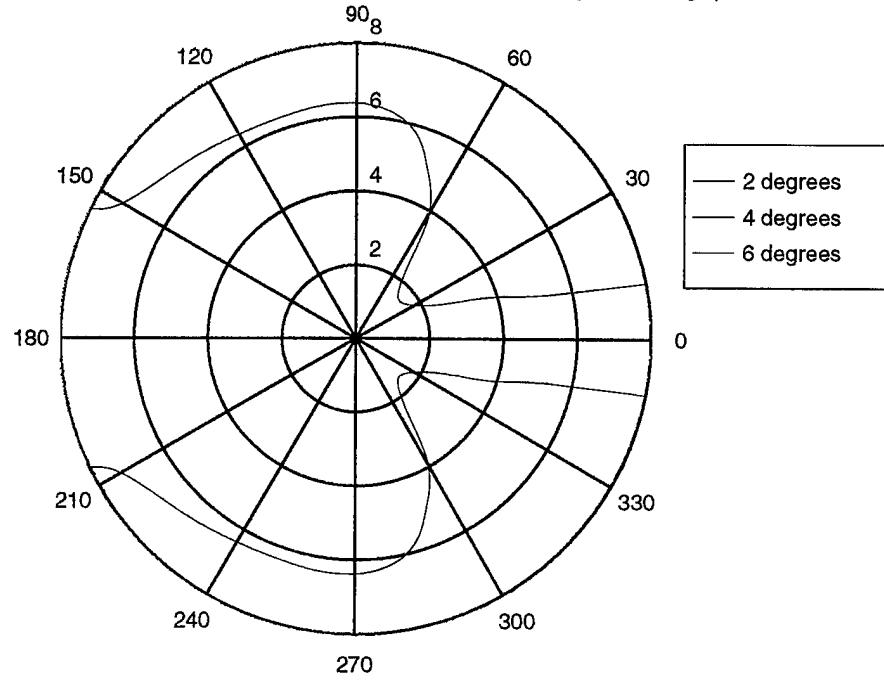


Figure 16. Sea state vs. wave angle for 150x3 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

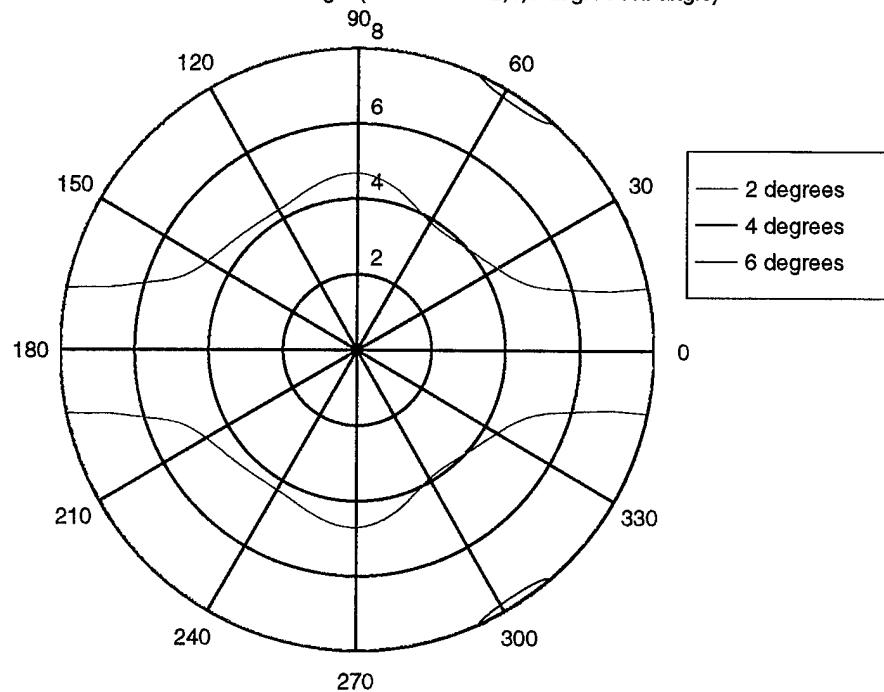


Figure 17. Sea state vs. wave angle for 150x2 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

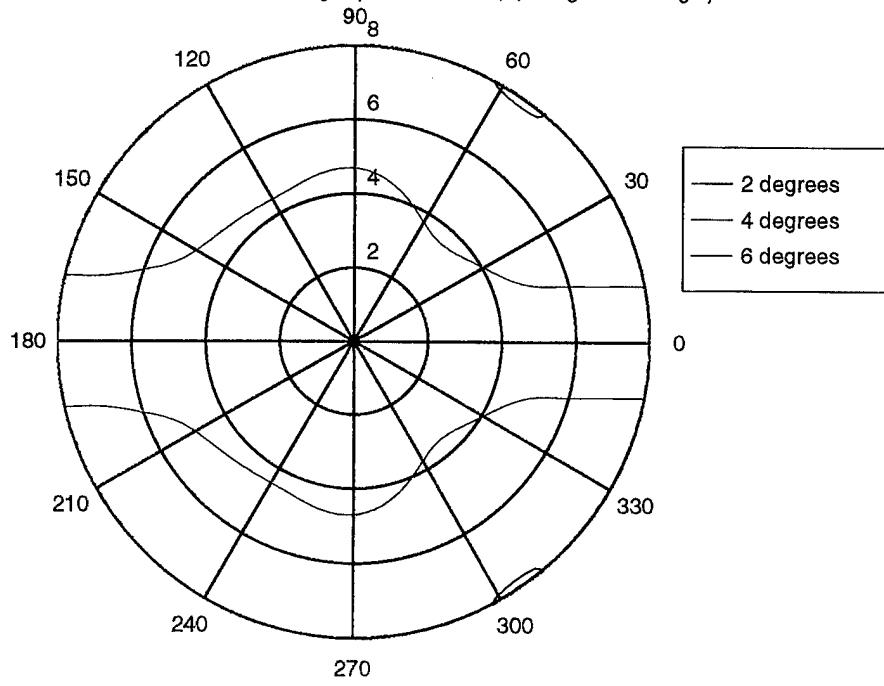


Figure 18. Sea state vs. wave angle for 150x2 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

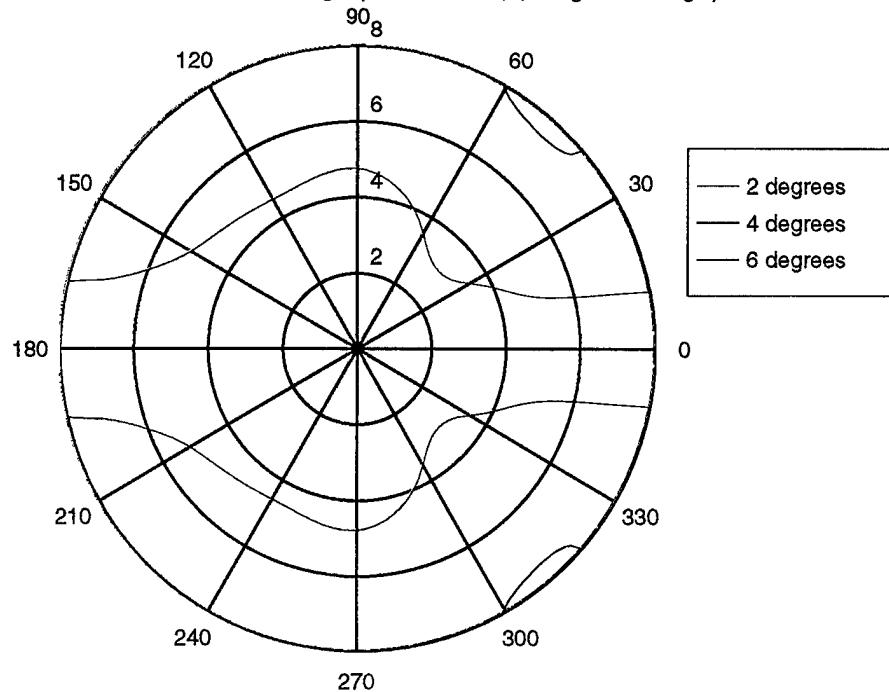


Figure 19. Sea state vs. wave angle for 150x2 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

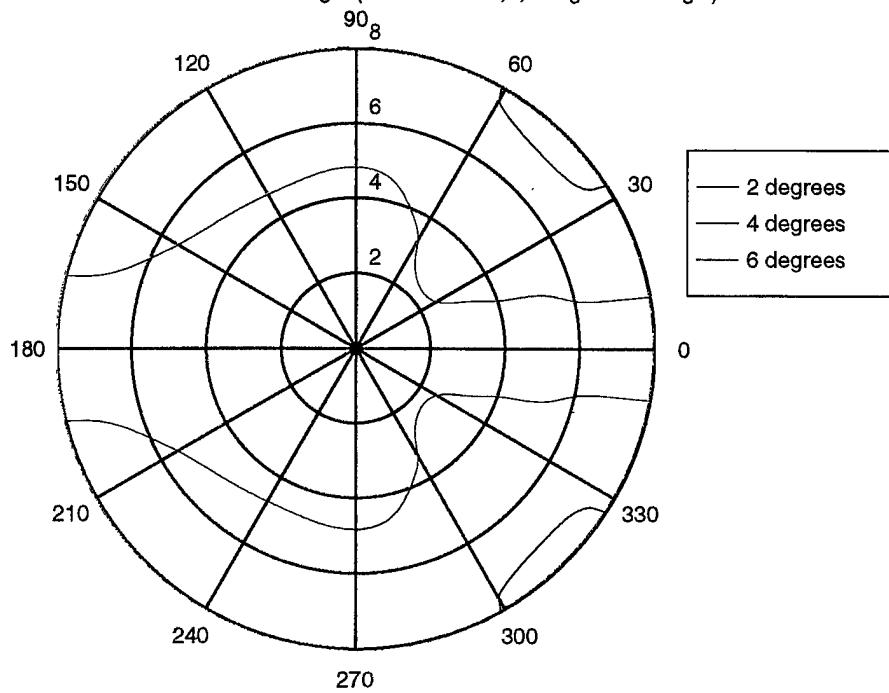


Figure 20. Sea state vs. wave angle for 150x2 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

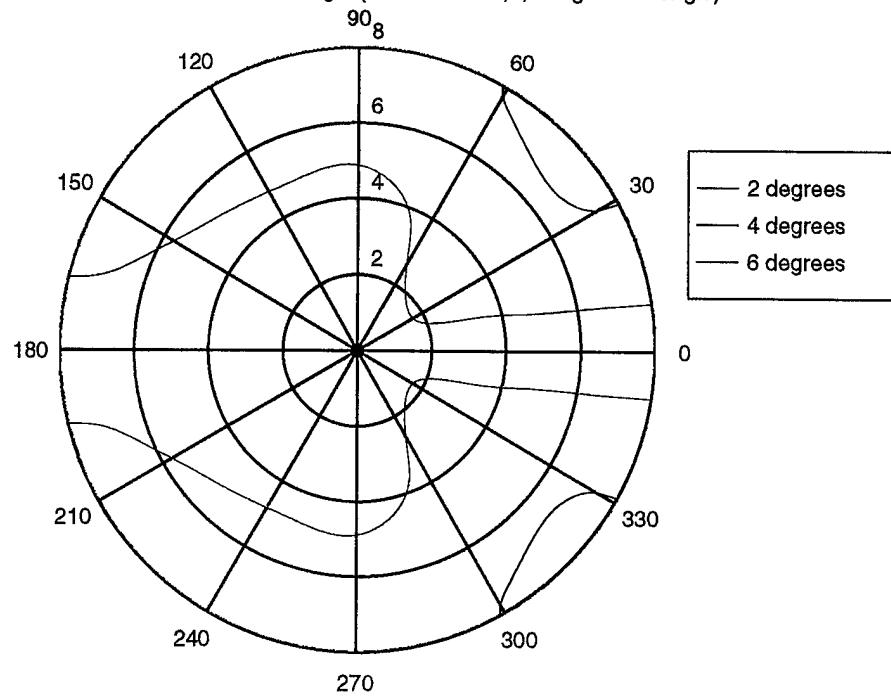


Figure 21. Sea state vs. wave angle for 150x2 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

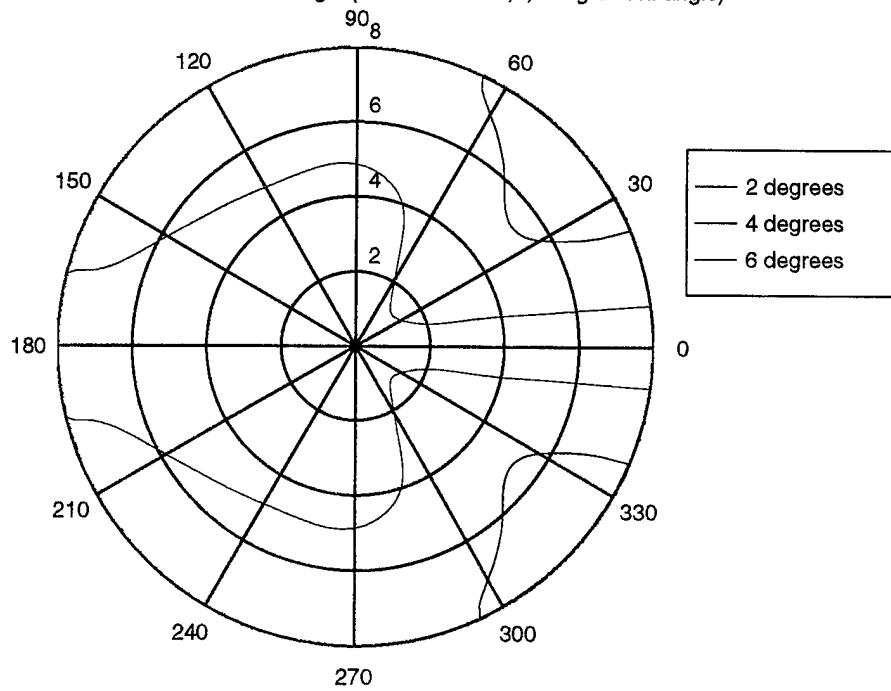


Figure 22. Sea state vs. wave angle for 150x2 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

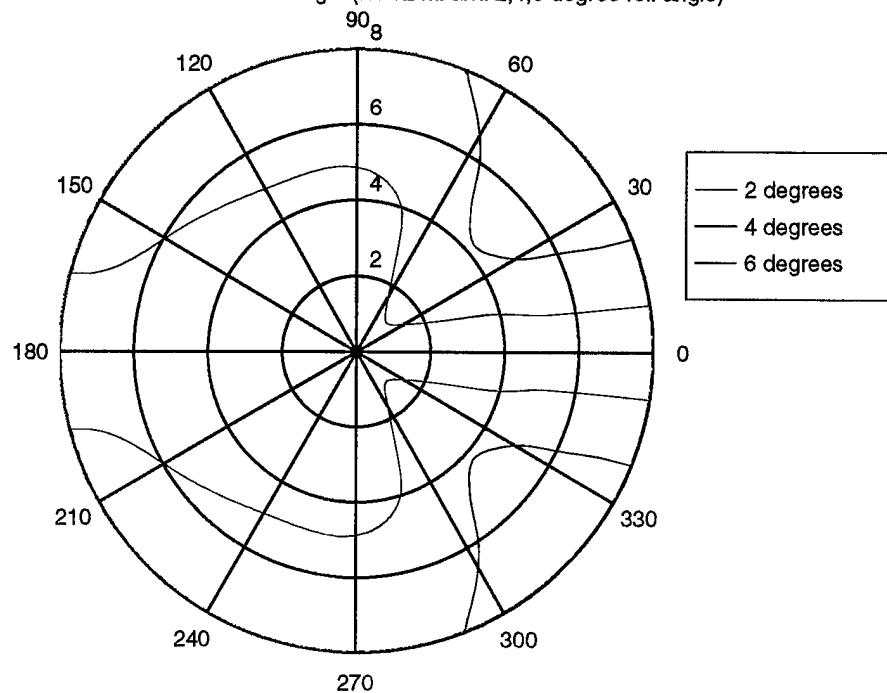


Figure 23. Sea state vs. wave angle for 150x2 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

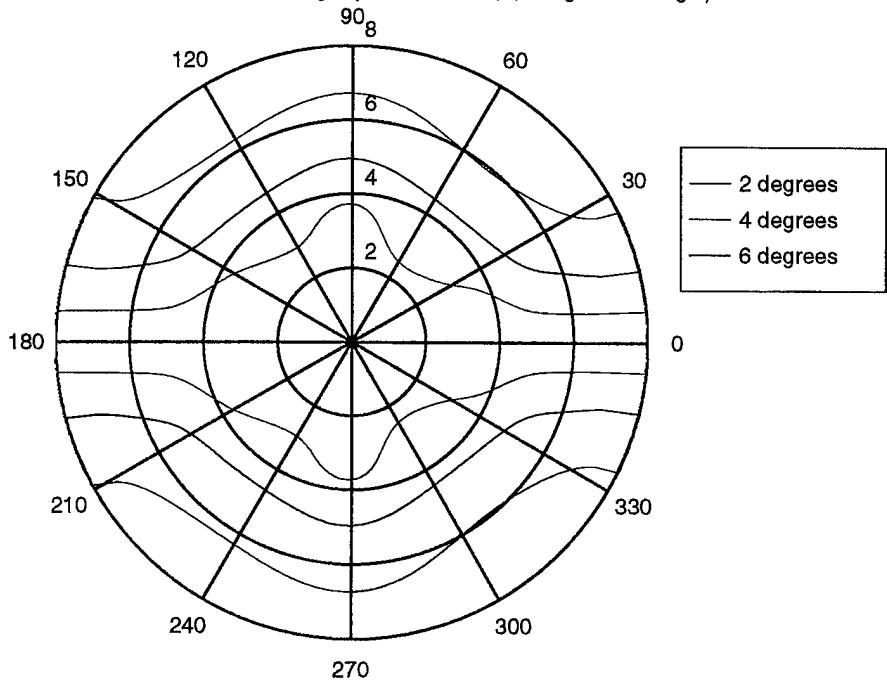


Figure 24. Sea state vs. wave angle for 150x1 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

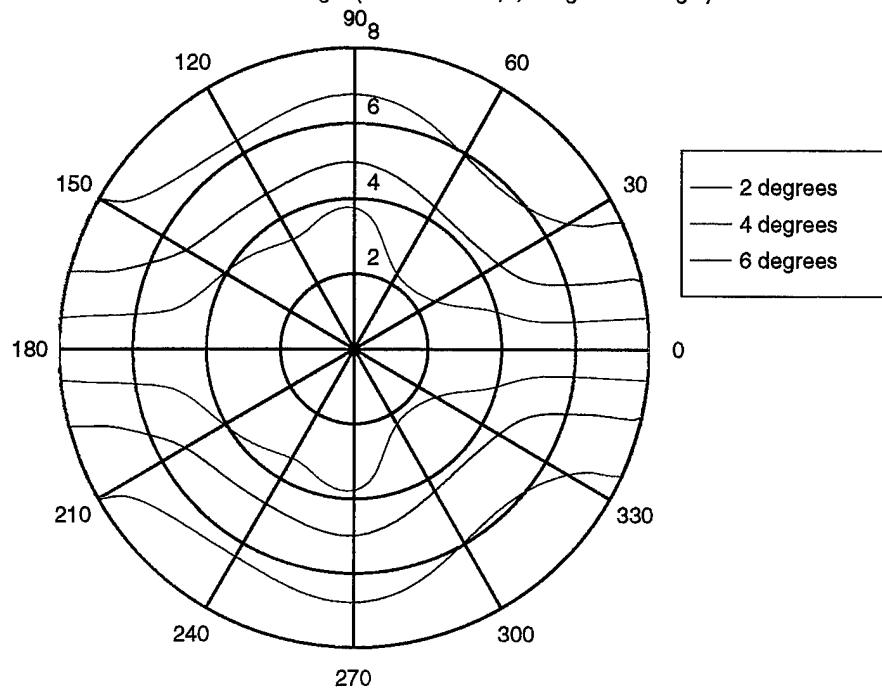


Figure 25. Sea state vs. wave angle for 150x1 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

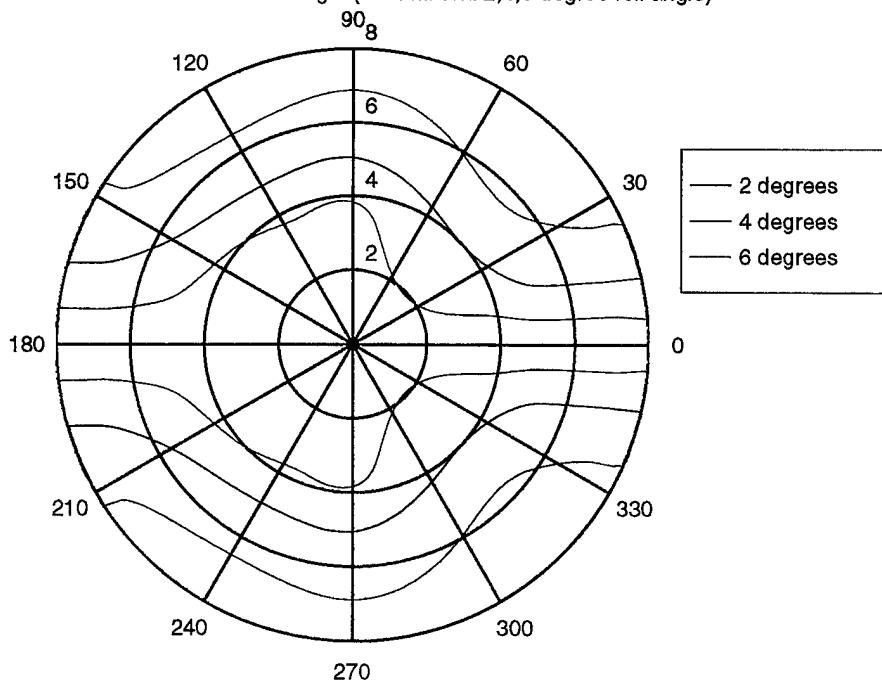


Figure 26. Sea state vs. wave angle for 150x1 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

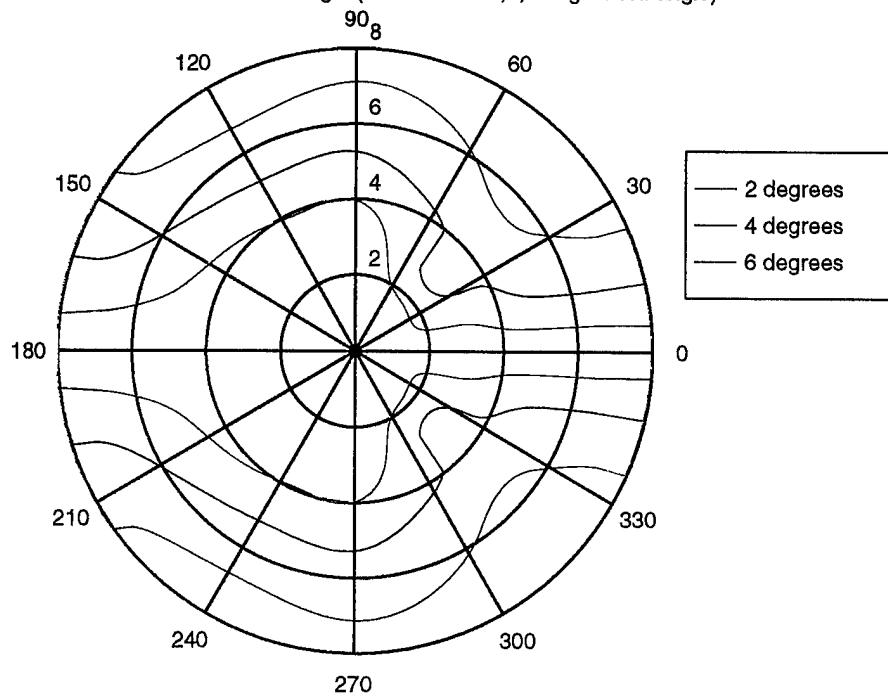


Figure 27. Sea state vs. wave angle for 150x1 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

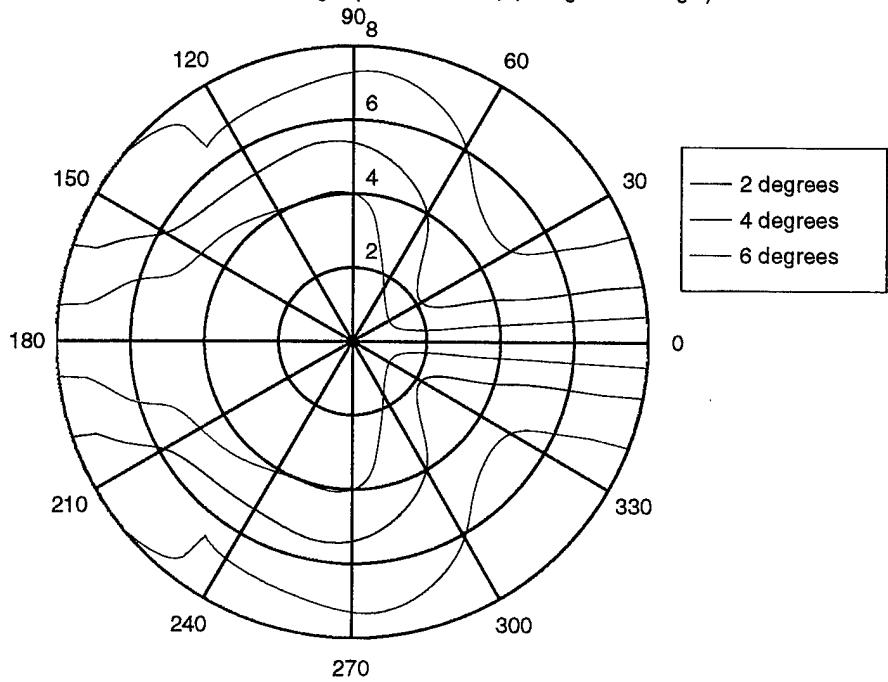


Figure 28. Sea state vs. wave angle for 150x1 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

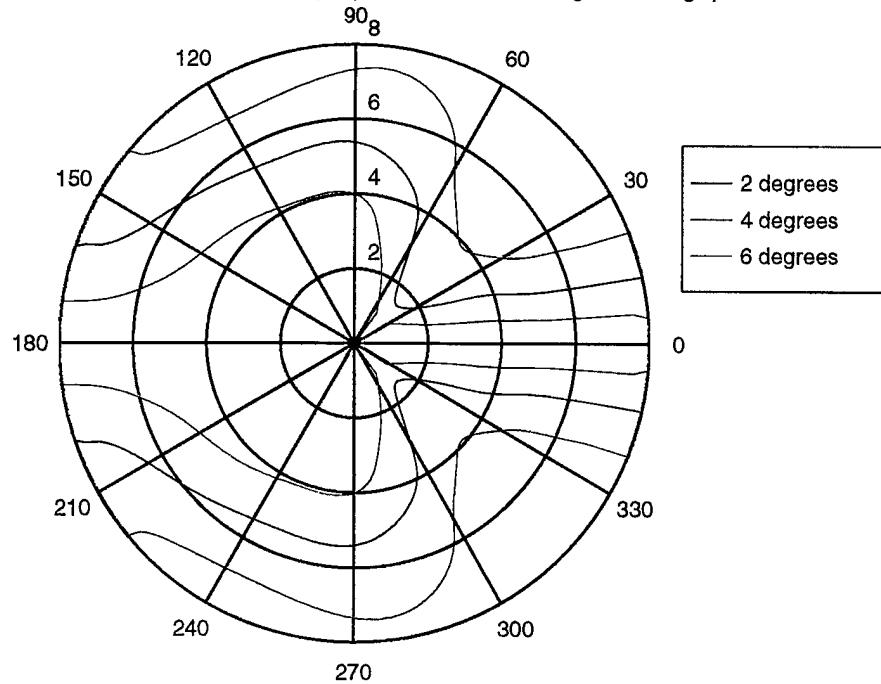


Figure 29. Sea state vs. wave angle for 150x1 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

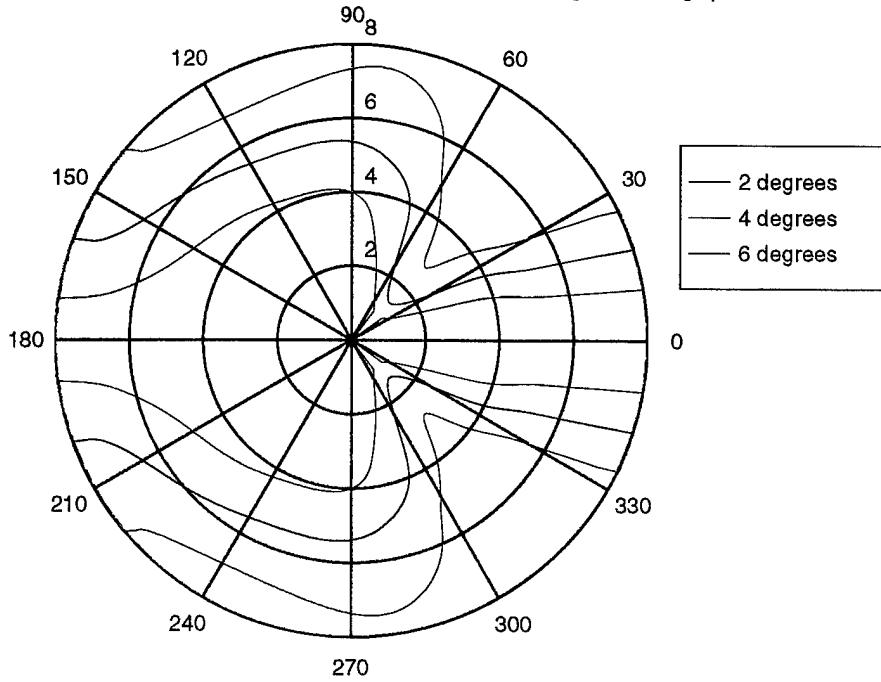


Figure 30. Sea state vs. wave angle for 150x1 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

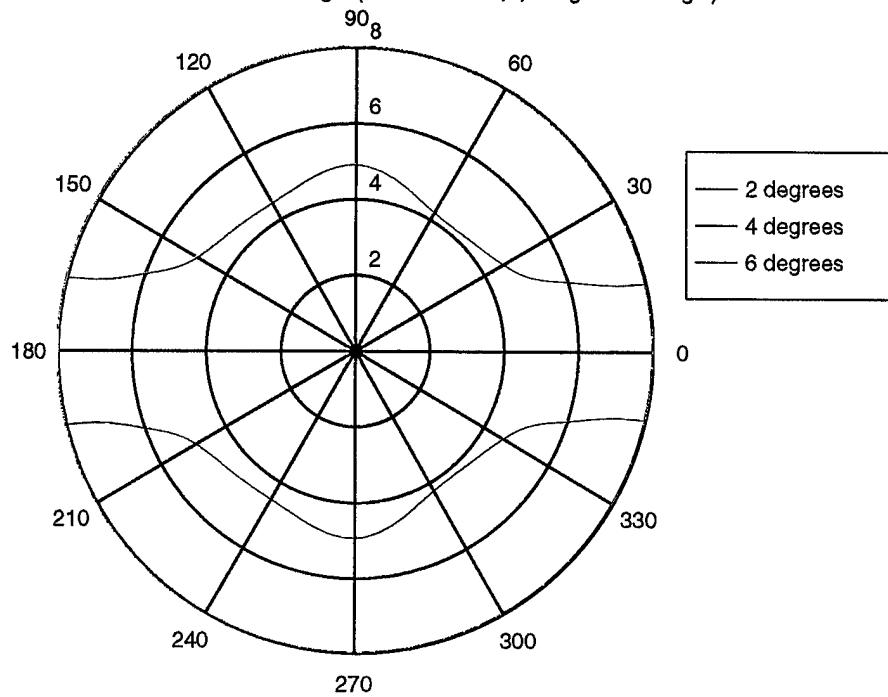


Figure 31. Sea state vs. wave angle for 75x3 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

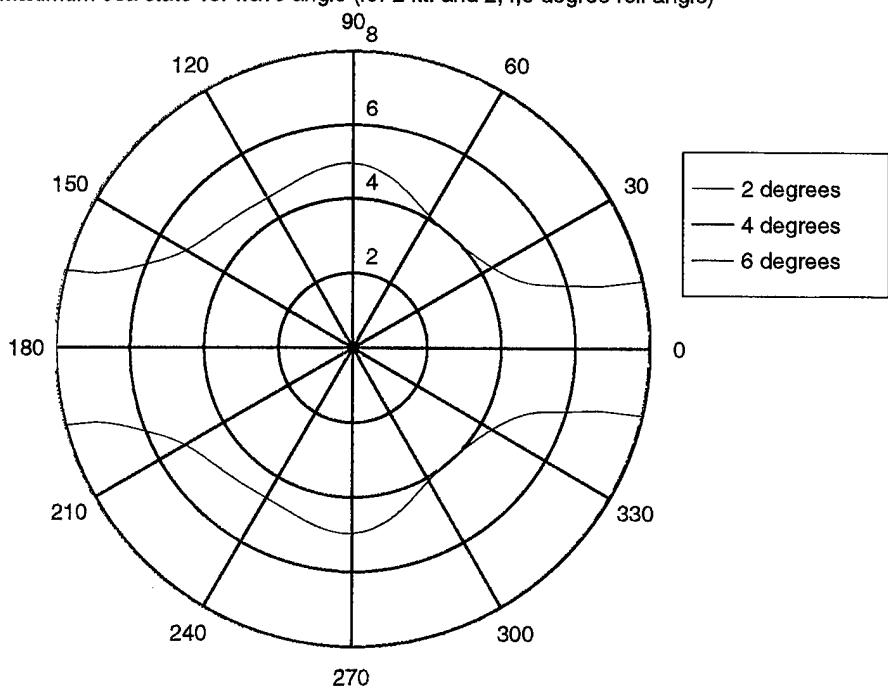


Figure 32. Sea state vs. wave angle for 75x3 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

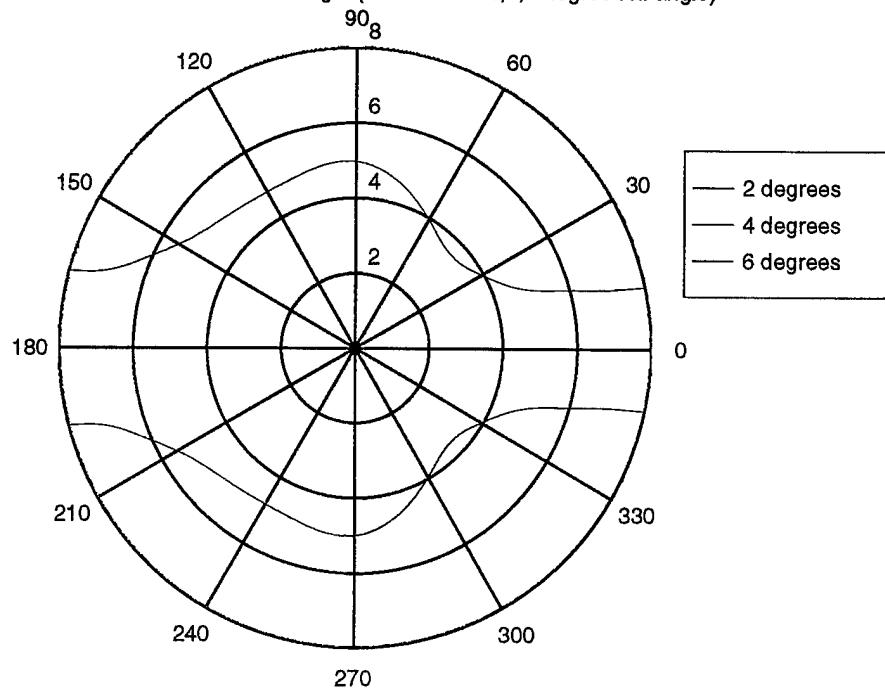


Figure 33. Sea state vs. wave angle for 75x3 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

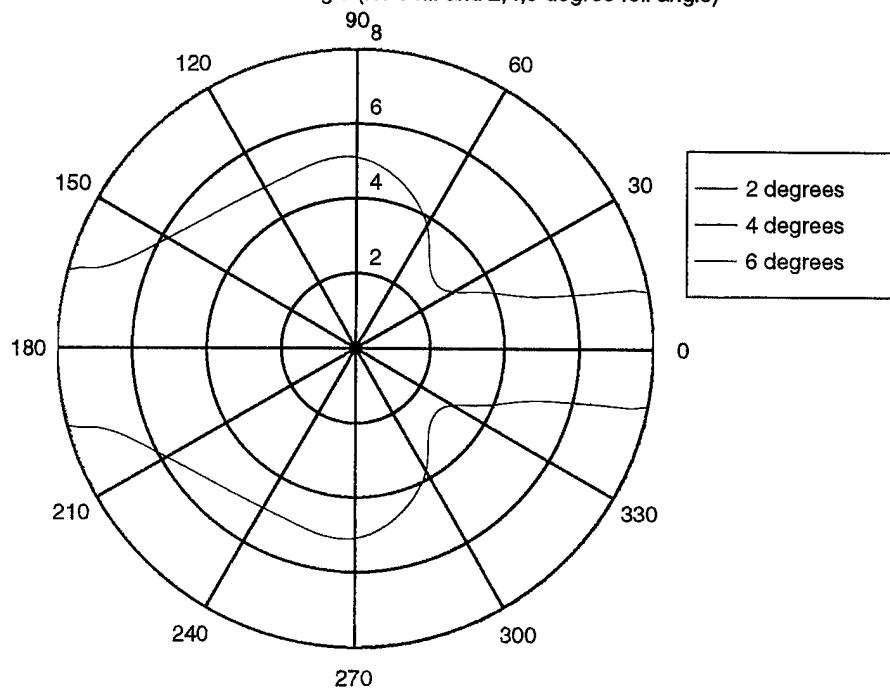


Figure 34. Sea state vs. wave angle for 75x3 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

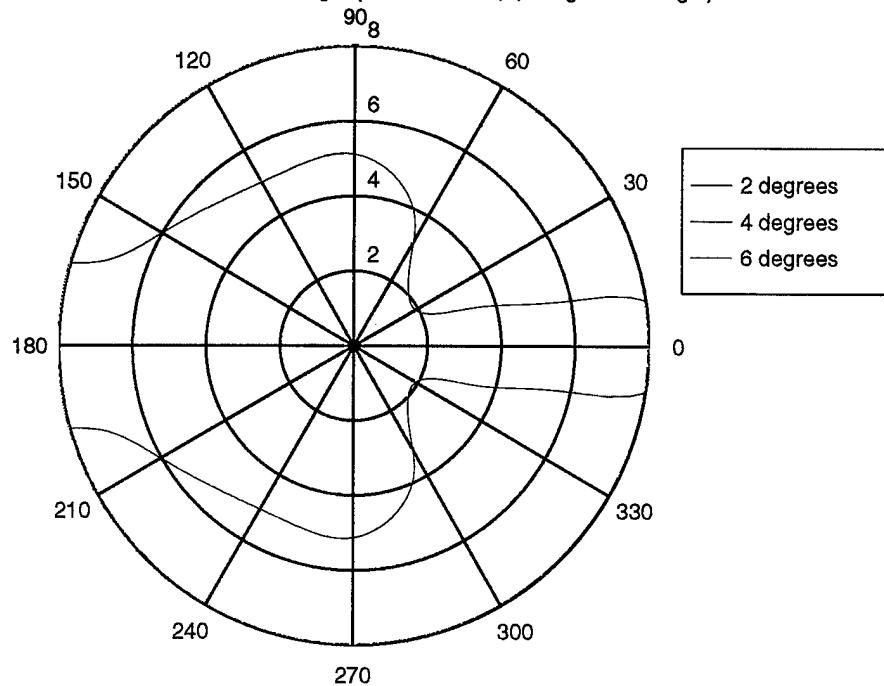


Figure 35. Sea state vs. wave angle for 75x3 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

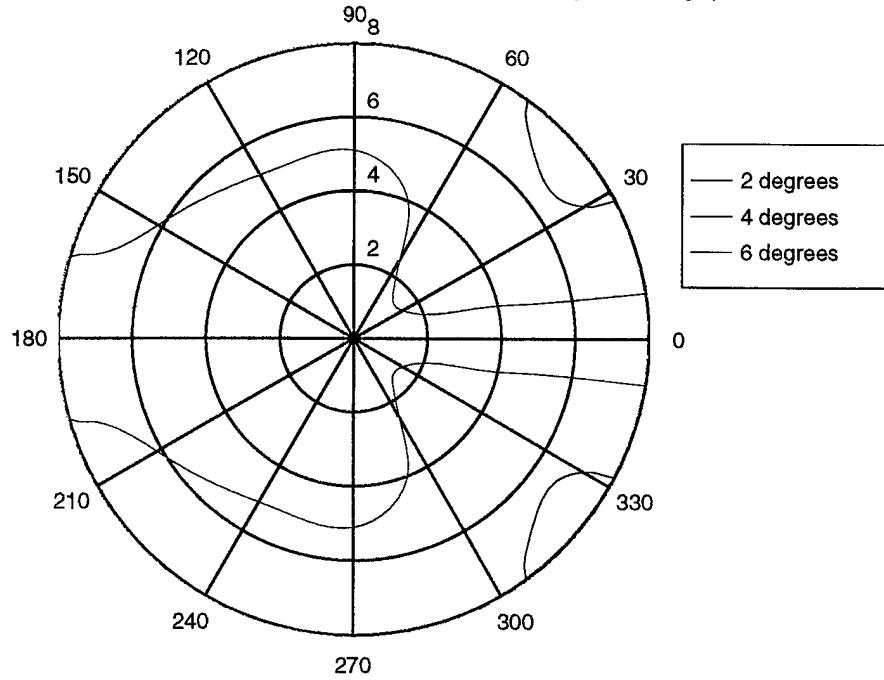


Figure 36. Sea state vs. wave angle for 75x3 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

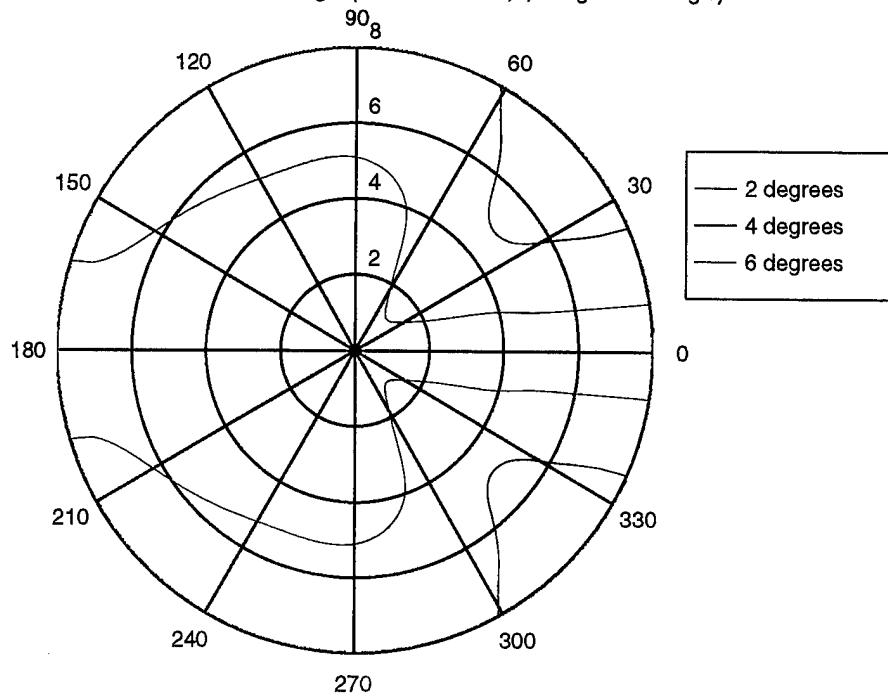


Figure 37. Sea state vs. wave angle for 75x3 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

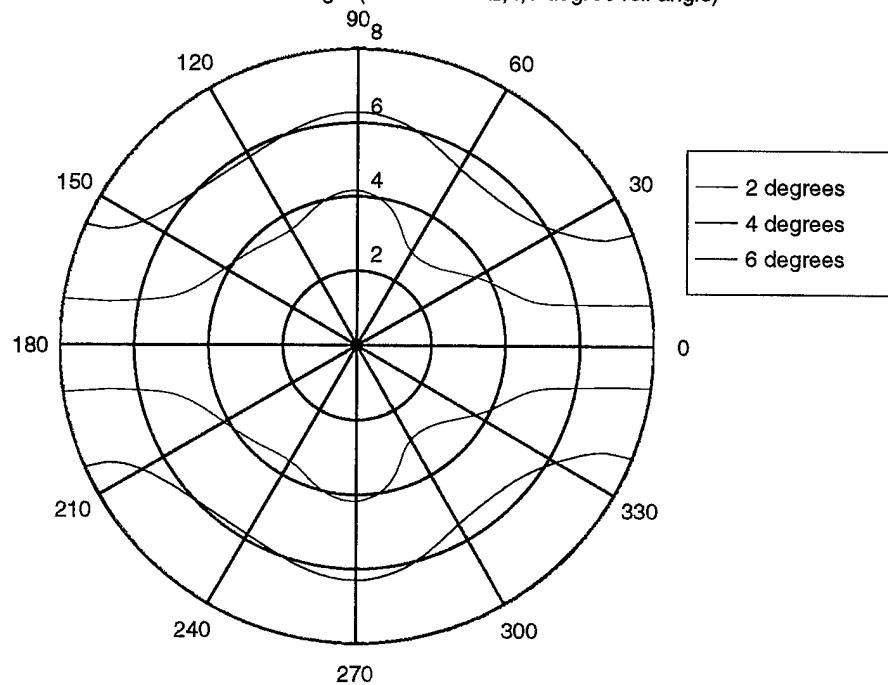


Figure 38. Sea state vs. wave angle for 75x2 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

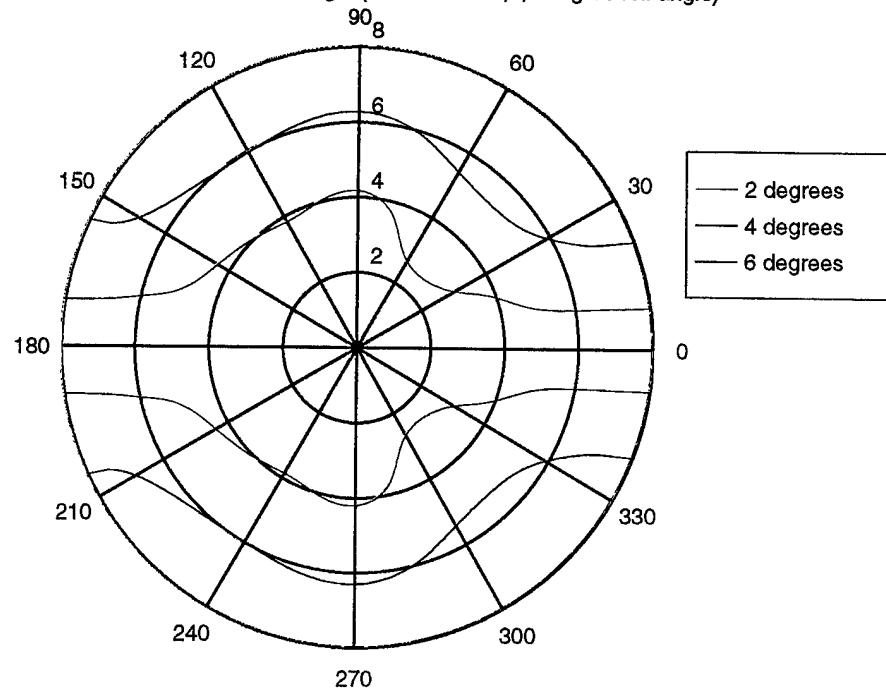


Figure 39. Sea state vs. wave angle for 75x2 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

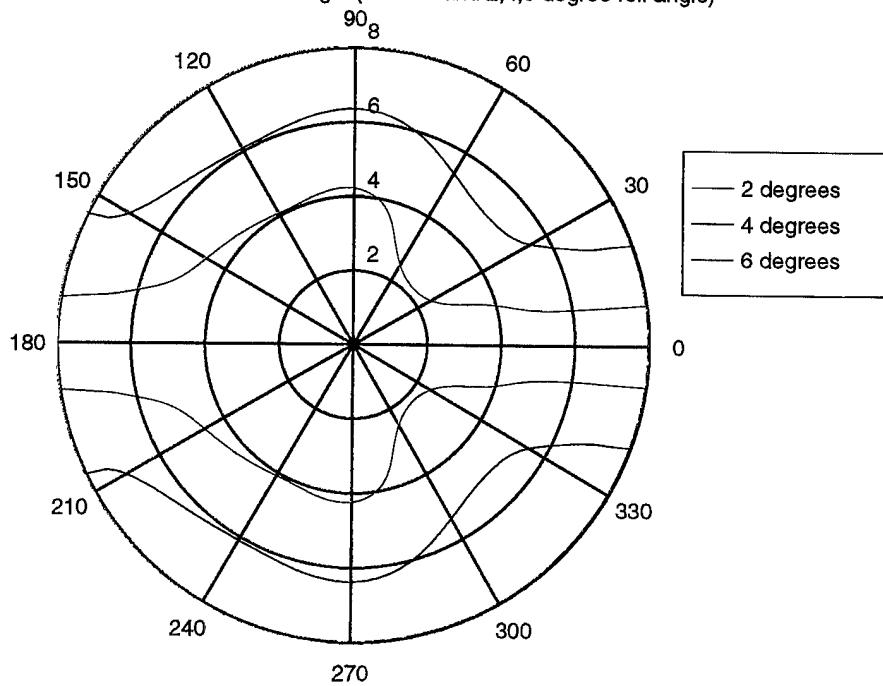


Figure 40. Sea state vs. wave angle for 75x2 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

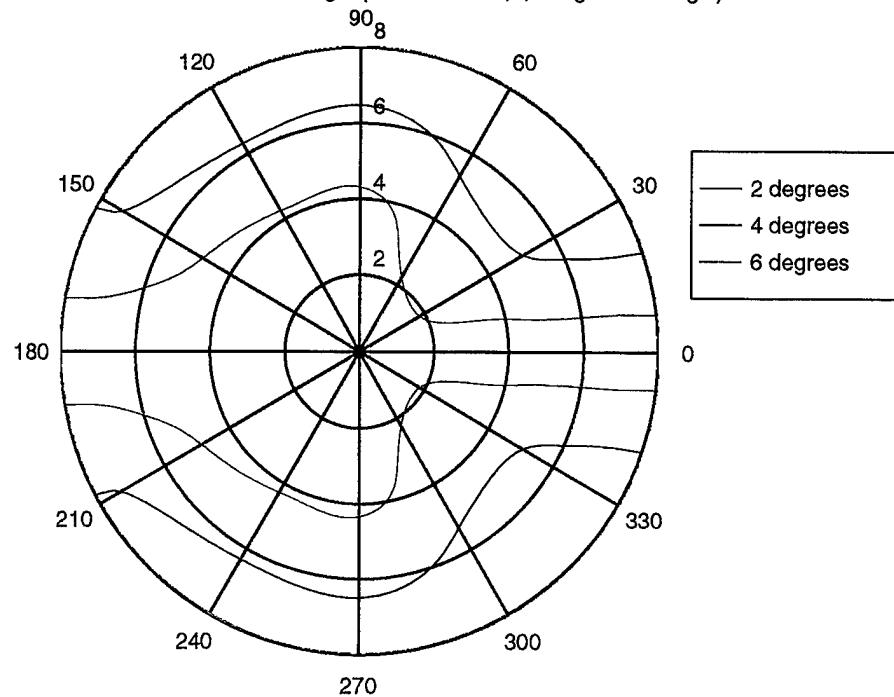


Figure 41. Sea state vs. wave angle for 75x2 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

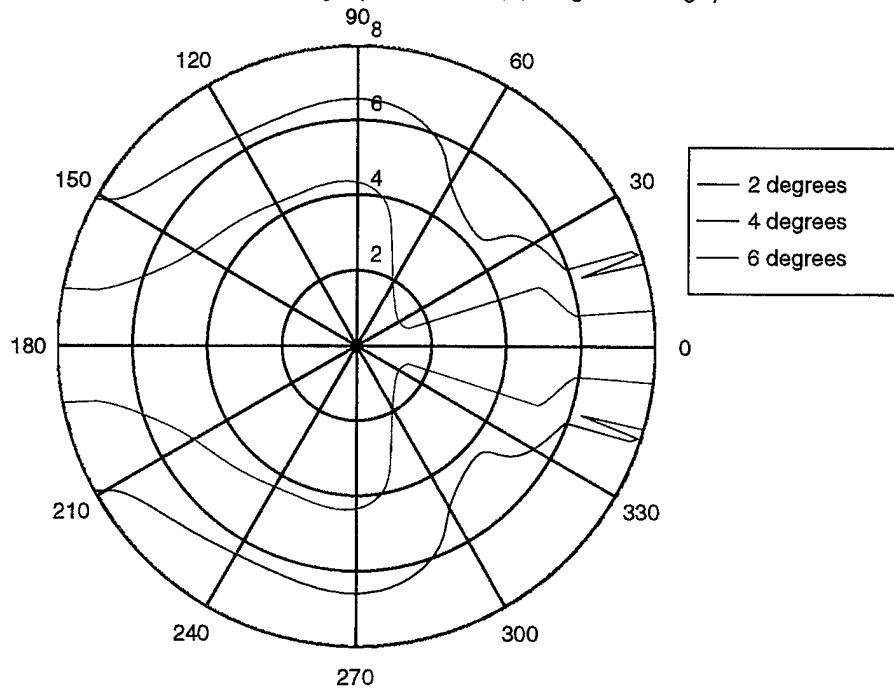


Figure 42. Sea state vs. wave angle for 75x2 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

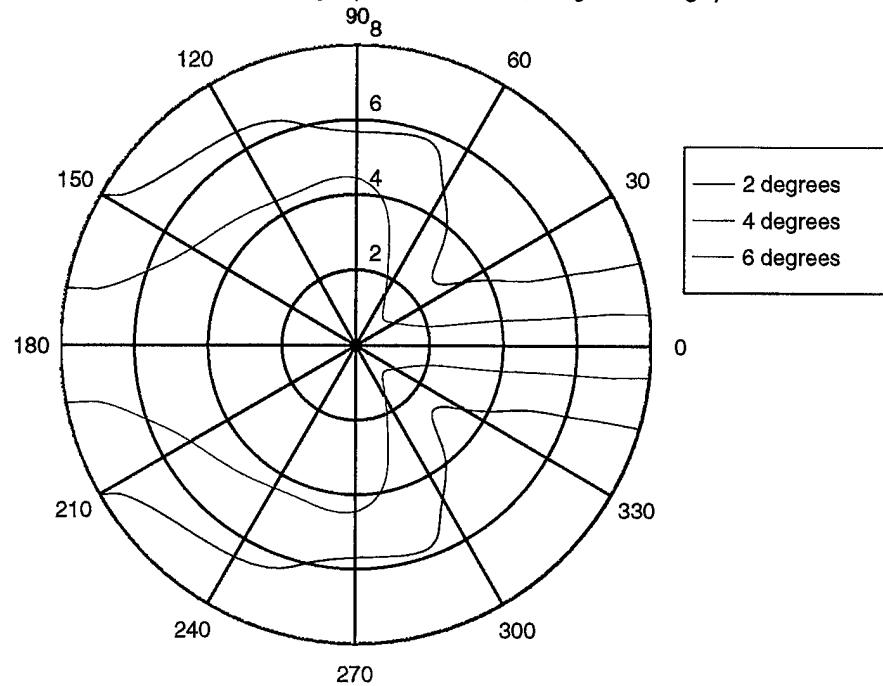


Figure 43. Sea state vs. wave angle for 75x2 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

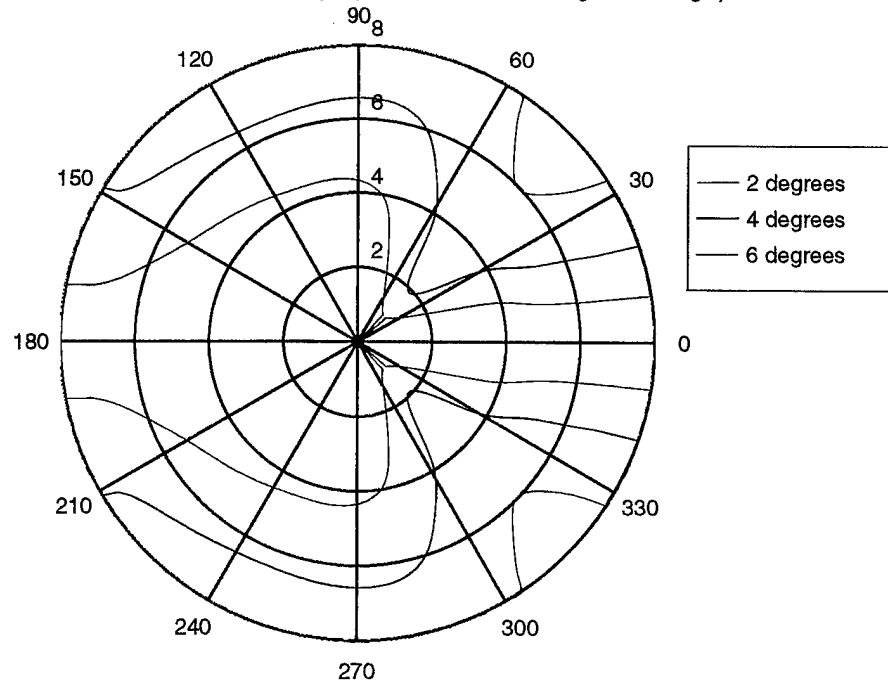


Figure 44. Sea state vs. wave angle for 75x2 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

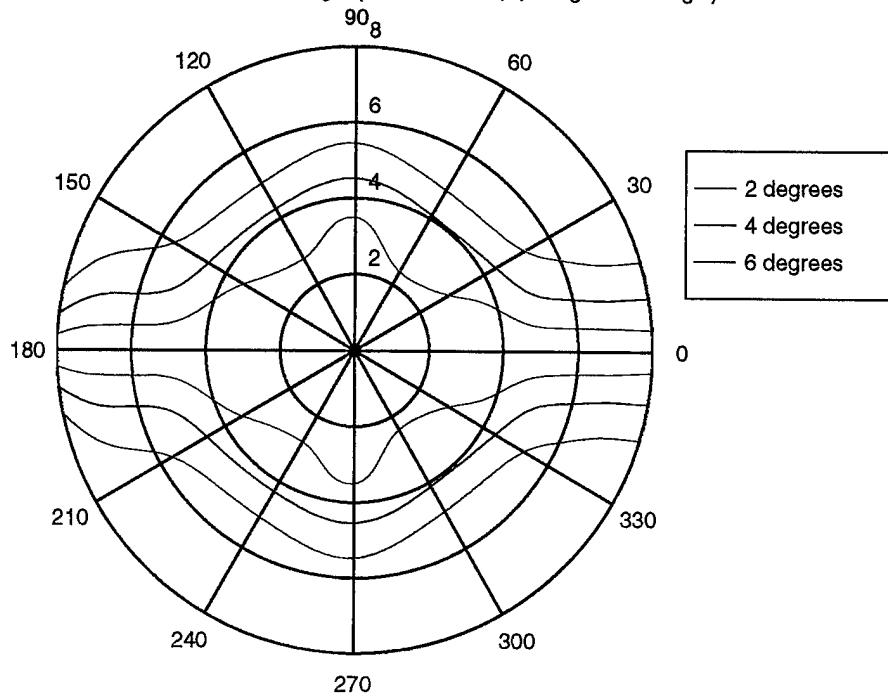


Figure 45. Sea state vs. wave angle for 75x1 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

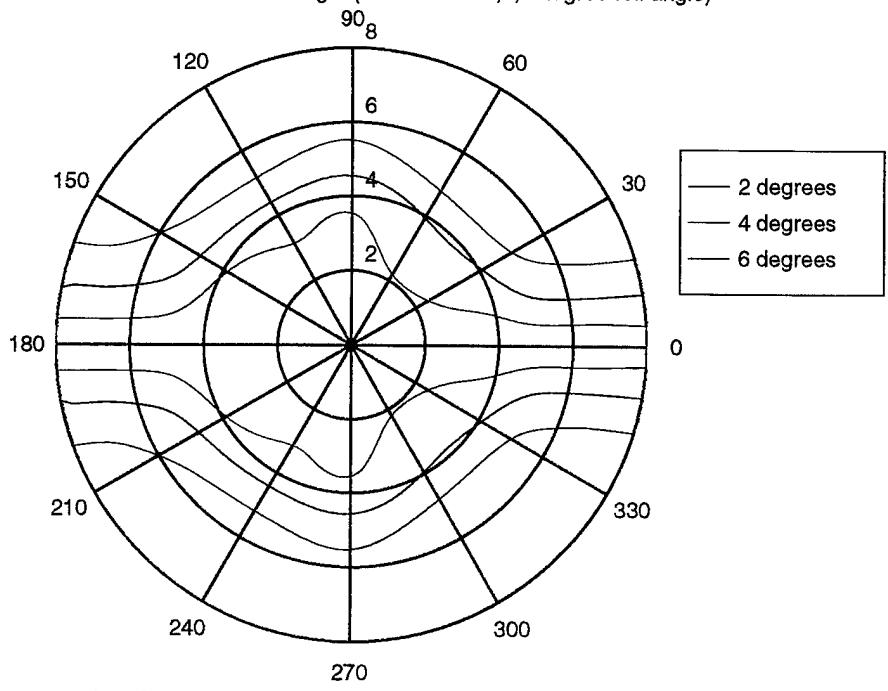


Figure 46. Sea state vs. wave angle for 75x1 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

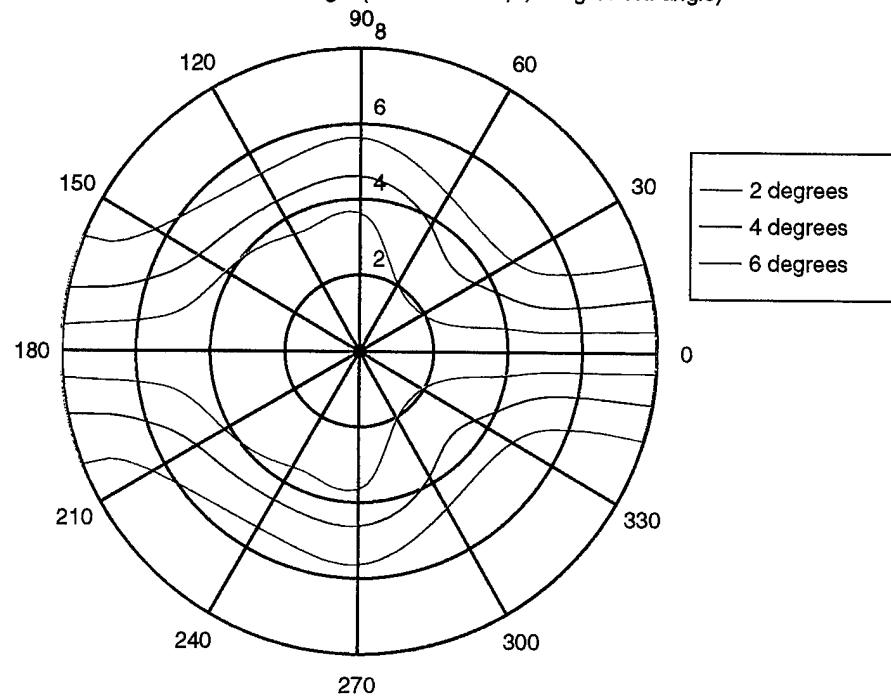


Figure 47. Sea state vs. wave angle for 75x1 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

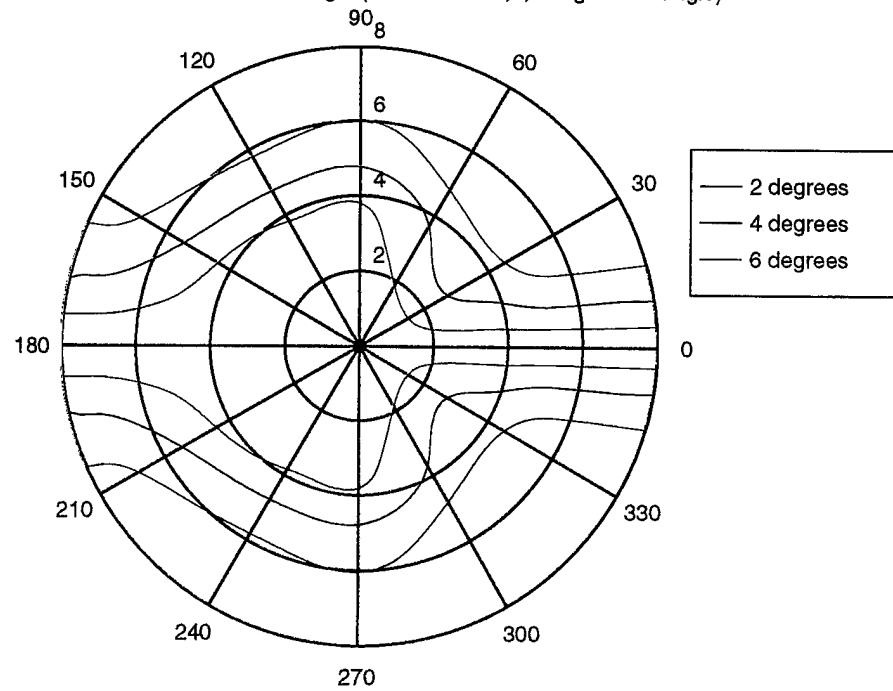


Figure 48. Sea state vs. wave angle for 75x1 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

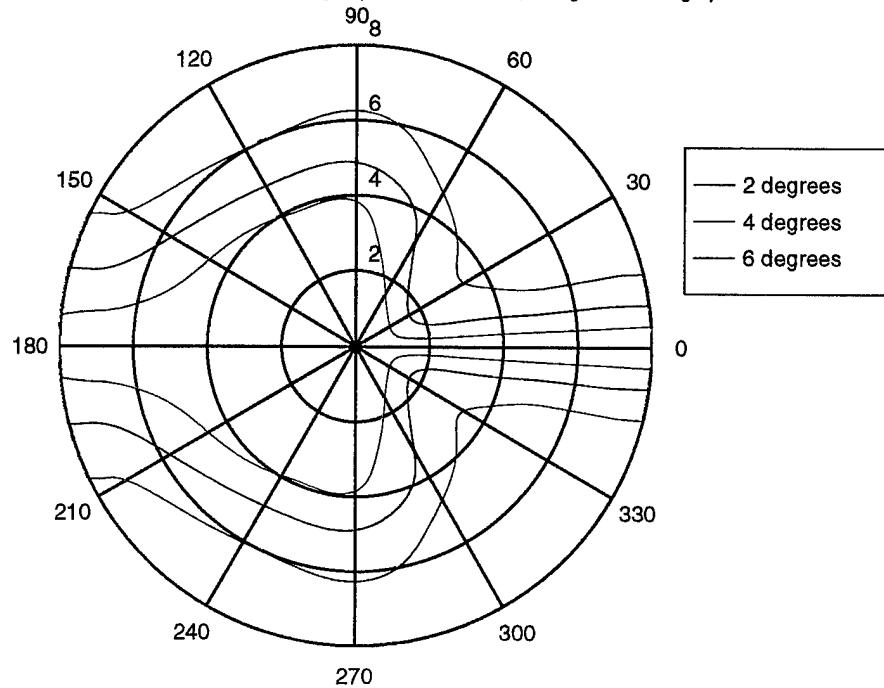


Figure 49. Sea state vs. wave angle for 75x1 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

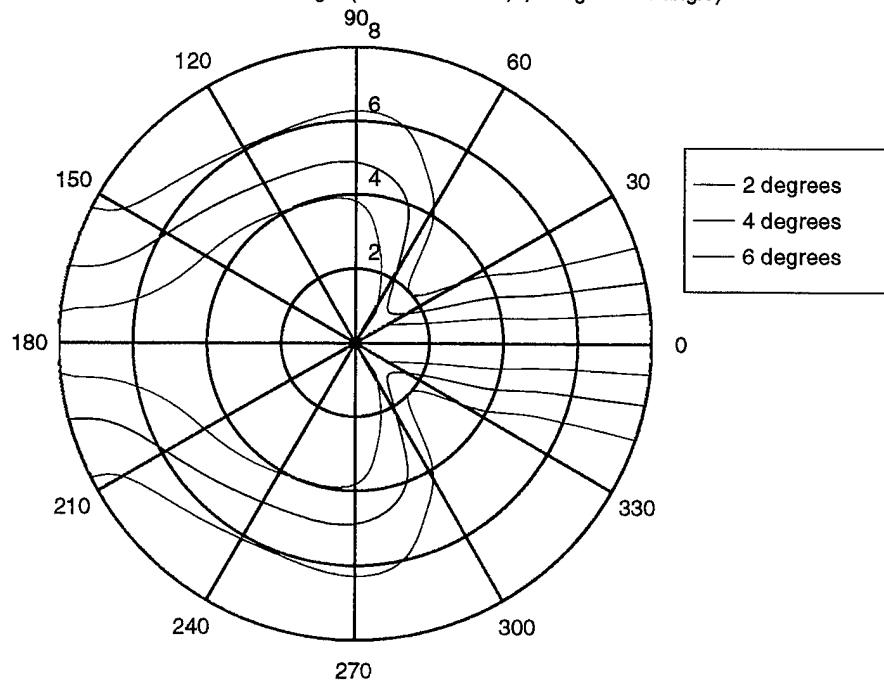


Figure 50. Sea state vs. wave angle for 75x1 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

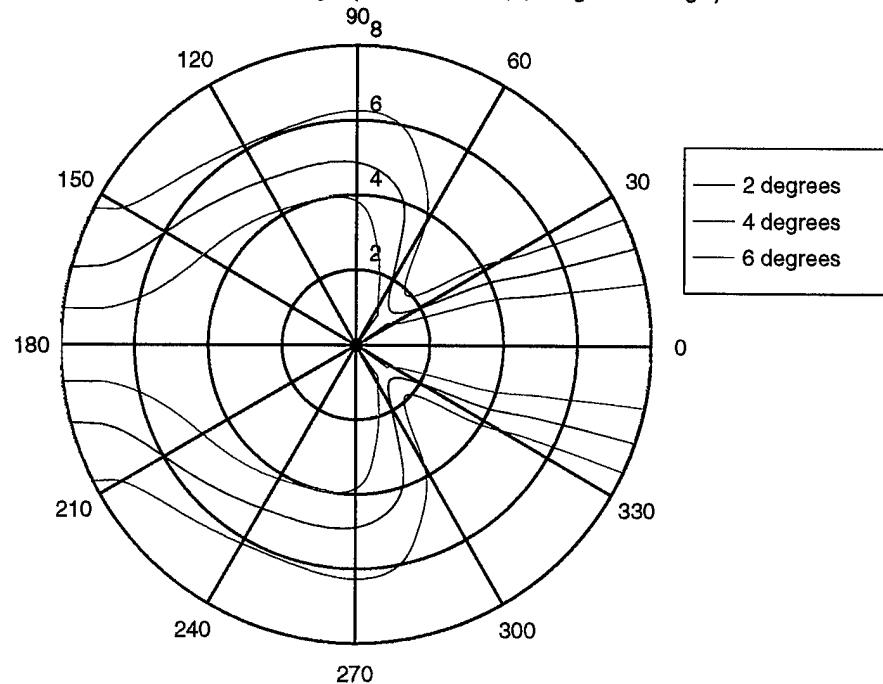


Figure 51. Sea state vs. wave angle for 75x1 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

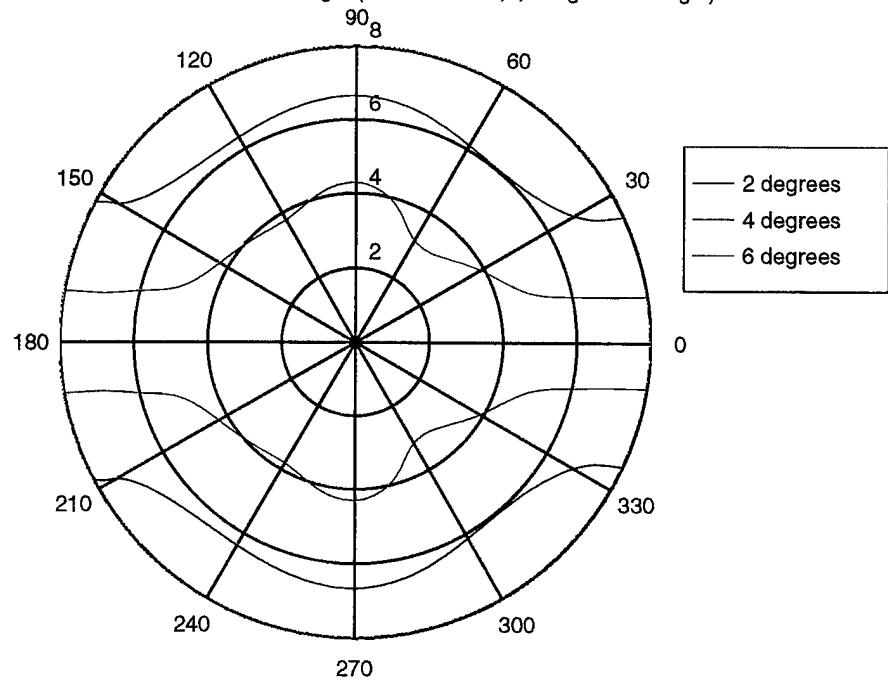


Figure 52. Sea state vs. wave angle for 37.5x3 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

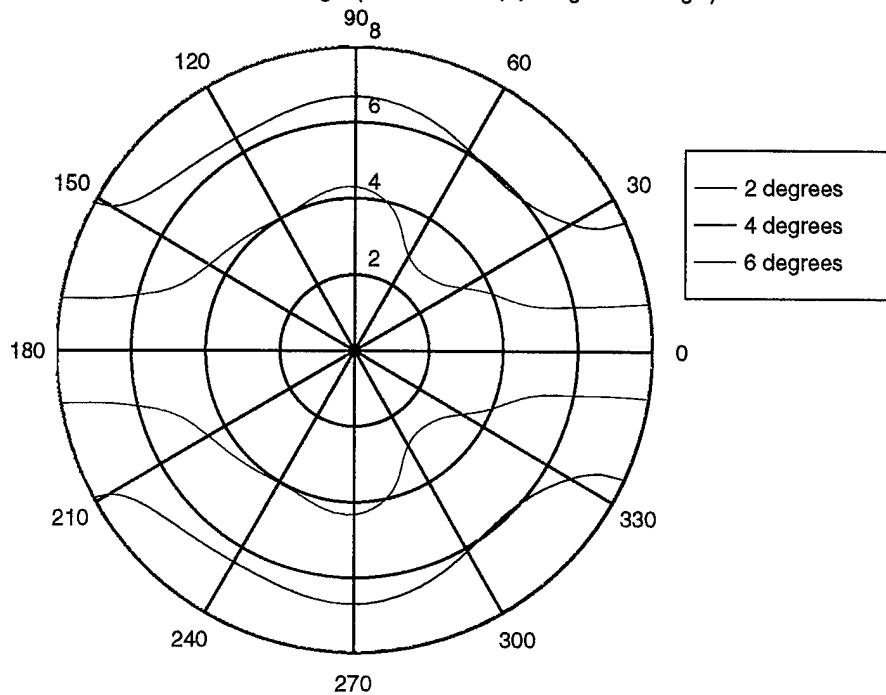


Figure 53. Sea state vs. wave angle for 37.5x3 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

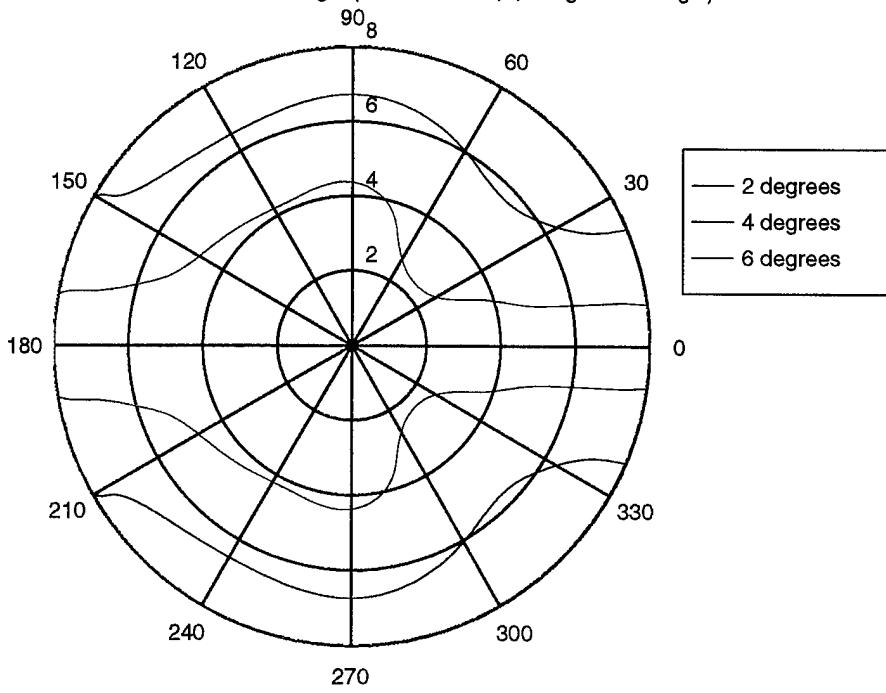


Figure 54. Sea state vs. wave angle for 37.5x3 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

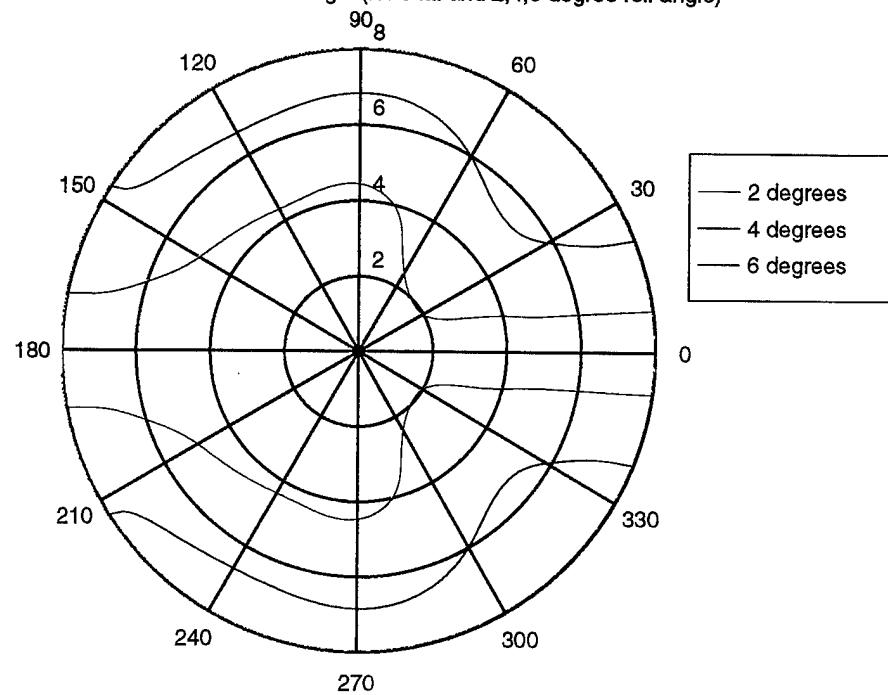


Figure 55. Sea state vs. wave angle for 37.5x3 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

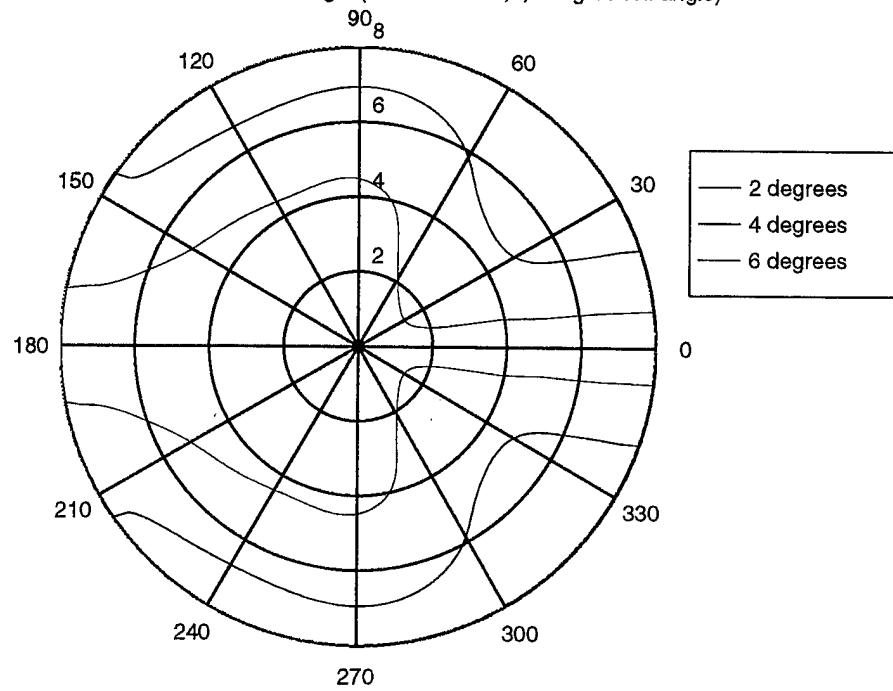


Figure 56. Sea state vs. wave angle for 37.5x3 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

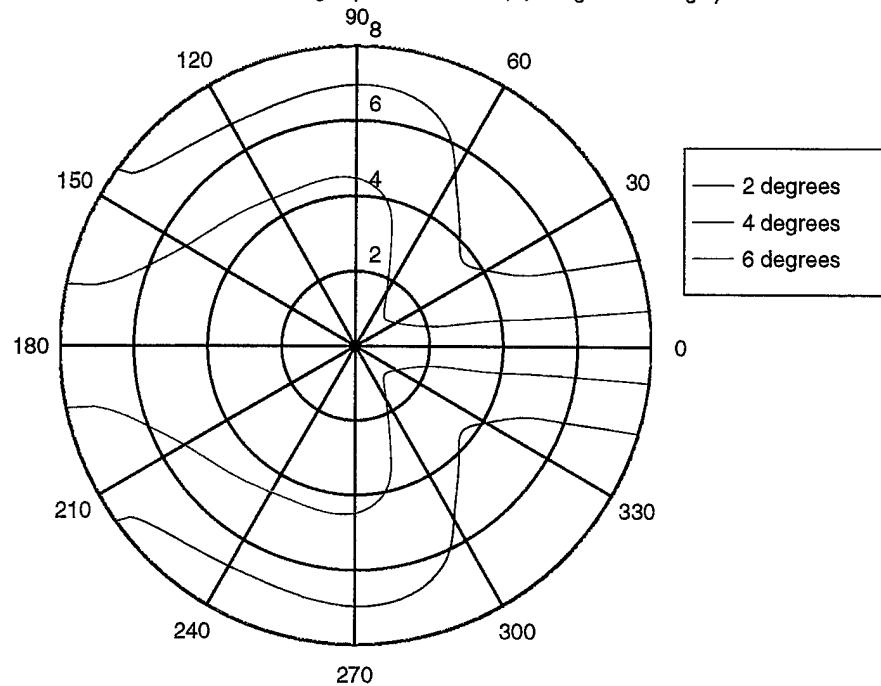


Figure 57. Sea state vs. wave angle for 37.5x3 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

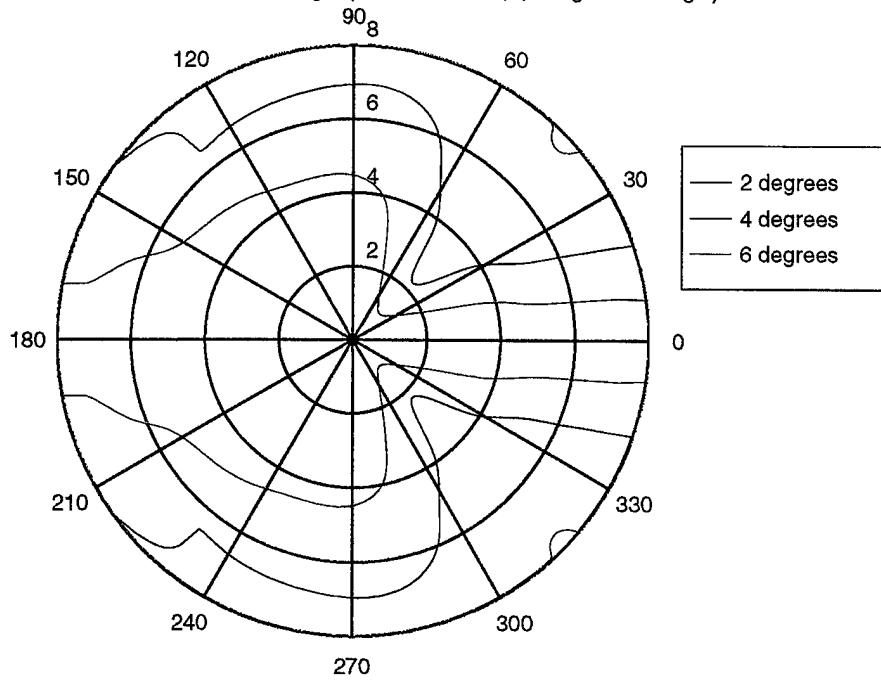


Figure 58. Sea state vs. wave angle for 37.5x3 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

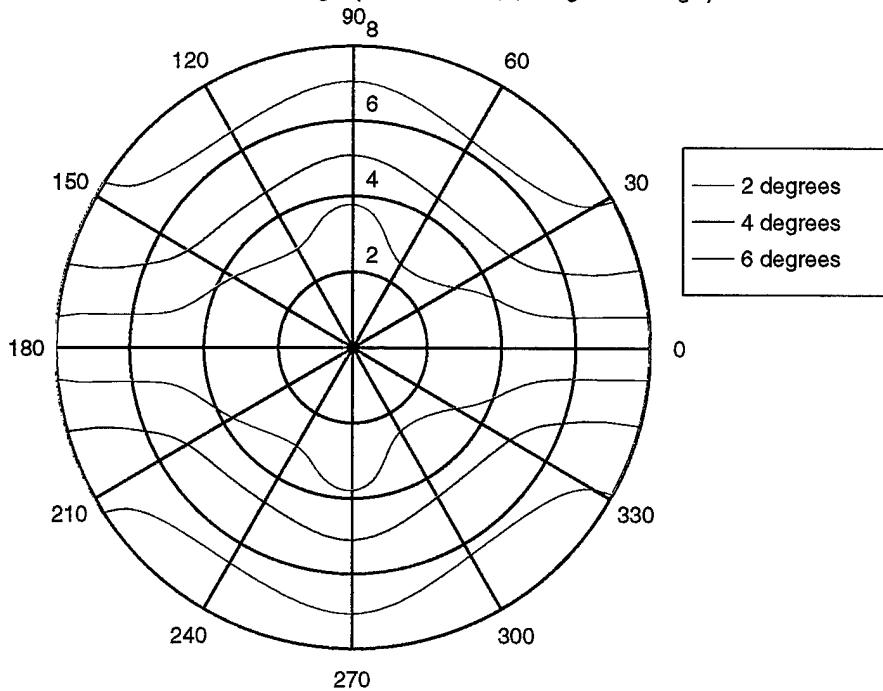


Figure 59. Sea state vs. wave angle for 37.5x2 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

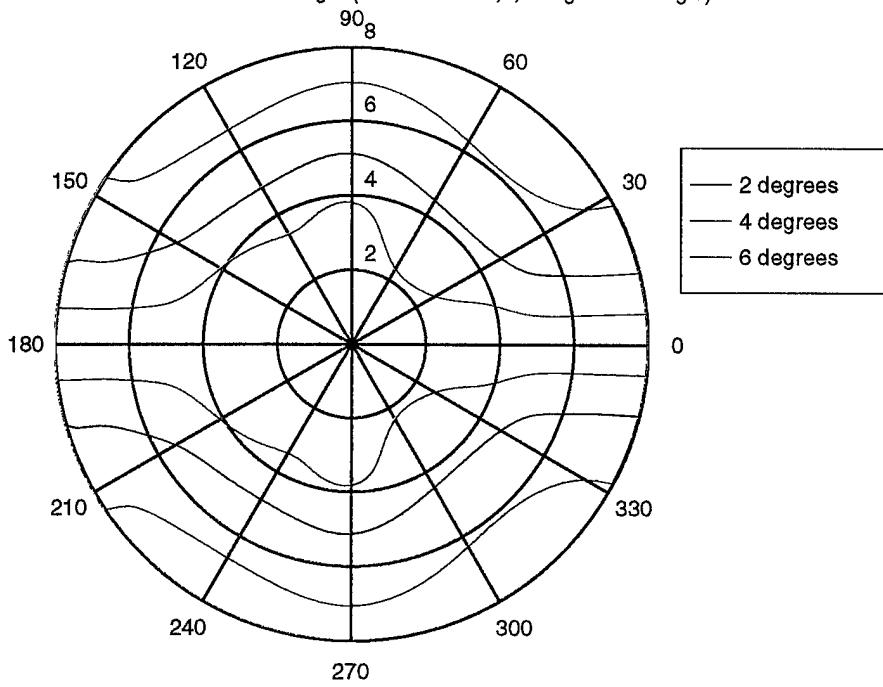


Figure 60. Sea state vs. wave angle for 37.5x2 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

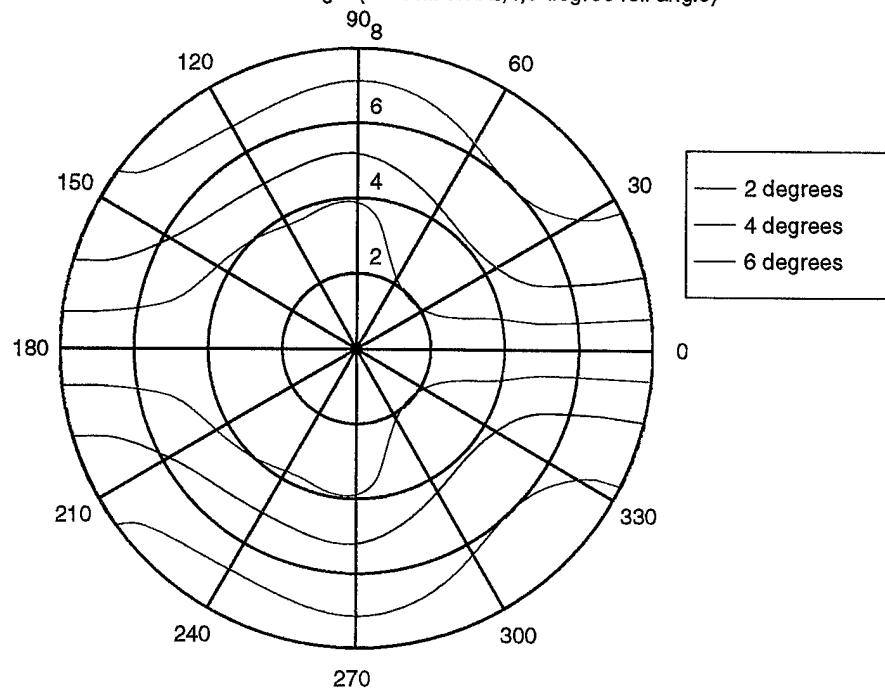


Figure 61. Sea state vs. wave angle for 37.5x2 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

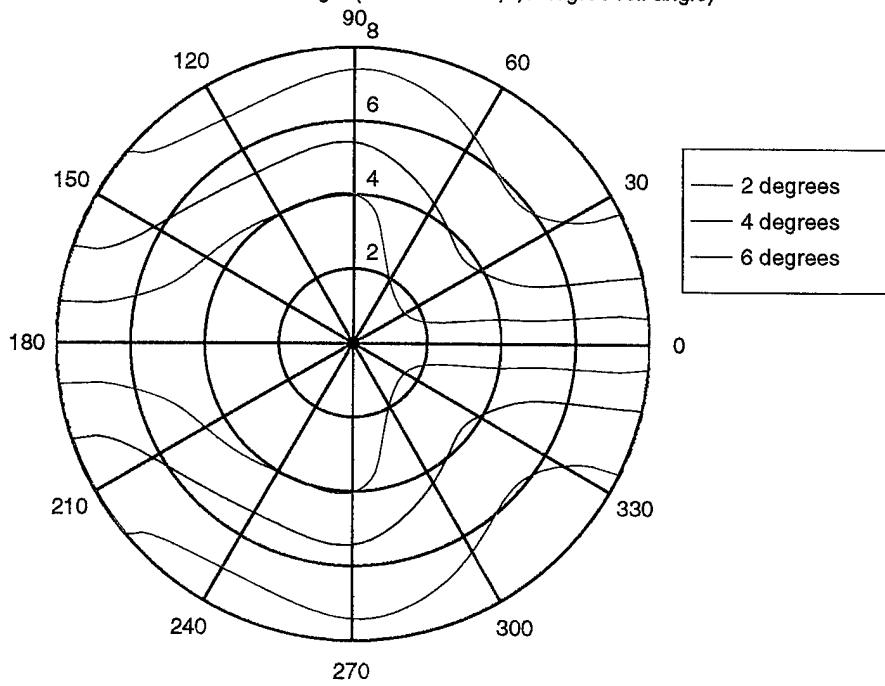


Figure 62. Sea state vs. wave angle for 37.5x2 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

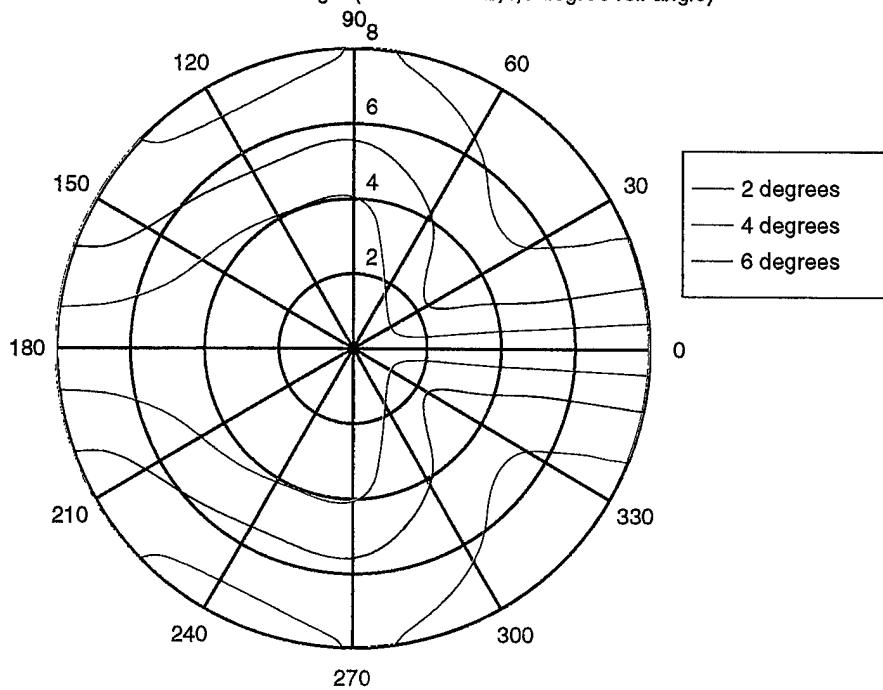


Figure 63. Sea state vs. wave angle for 37.5x2 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

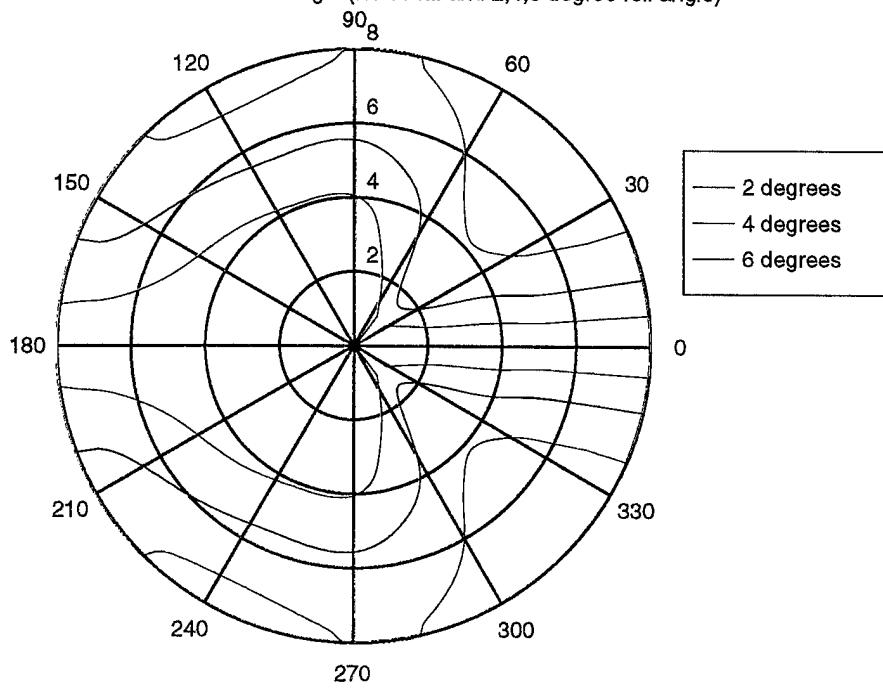


Figure 64. Sea state vs. wave angle for 37.5x2 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

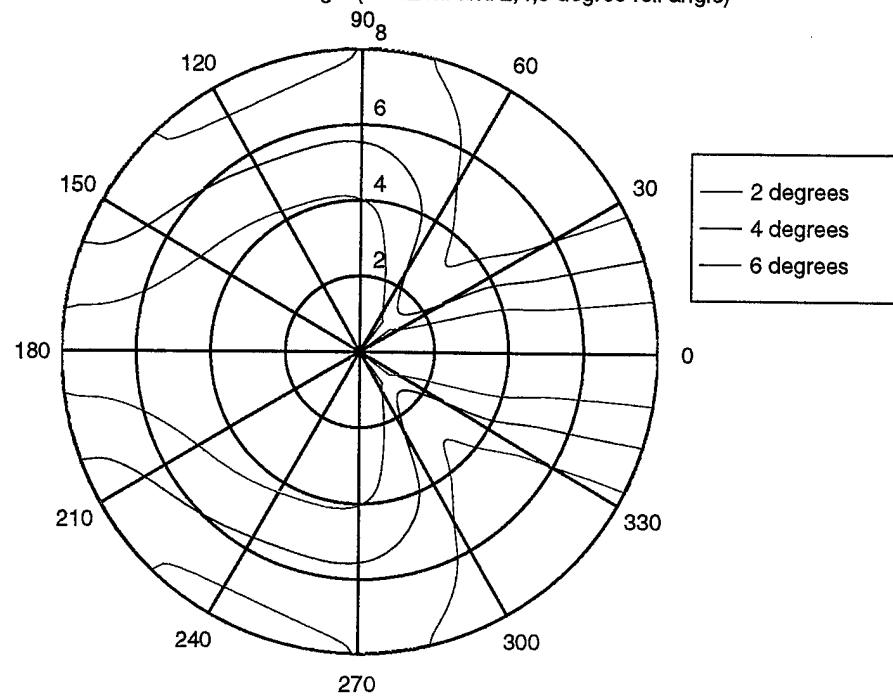


Figure 65. Sea state vs. wave angle for 37.5x2 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for 0 kt. and 2,4,6 degree roll angle)

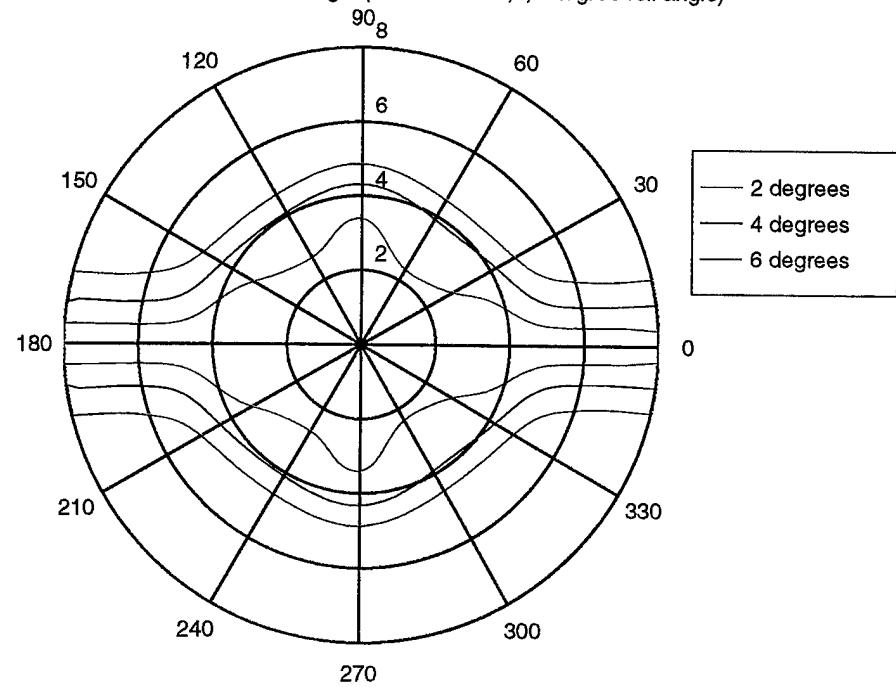


Figure 66. Sea state vs. wave angle for 37.5x1 bilge keel - 0 kts.

Maximum sea state vs. wave angle (for 2 kt. and 2,4,6 degree roll angle)

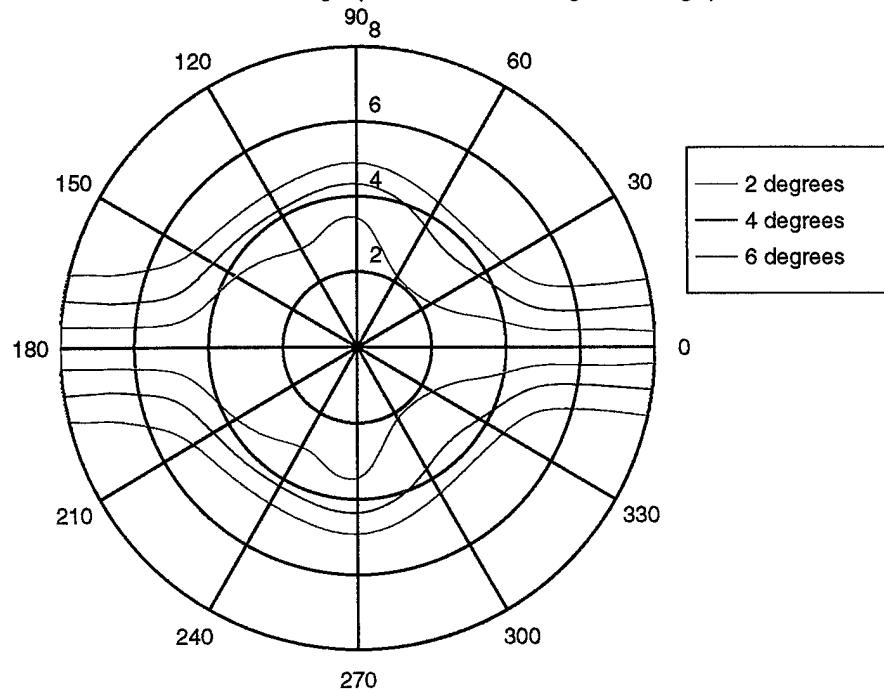


Figure 67. Sea state vs. wave angle for 37.5x1 bilge keel - 2 kts.

Maximum sea state vs. wave angle (for 4 kt. and 2,4,6 degree roll angle)

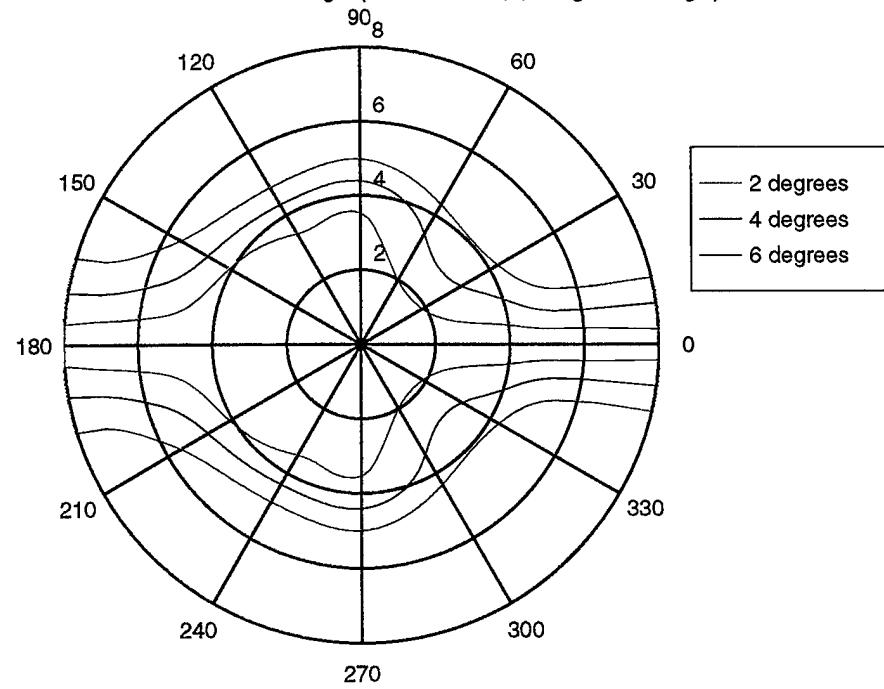


Figure 68. Sea state vs. wave angle for 37.5x1 bilge keel - 4 kts.

Maximum sea state vs. wave angle (for 6 kt. and 2,4,6 degree roll angle)

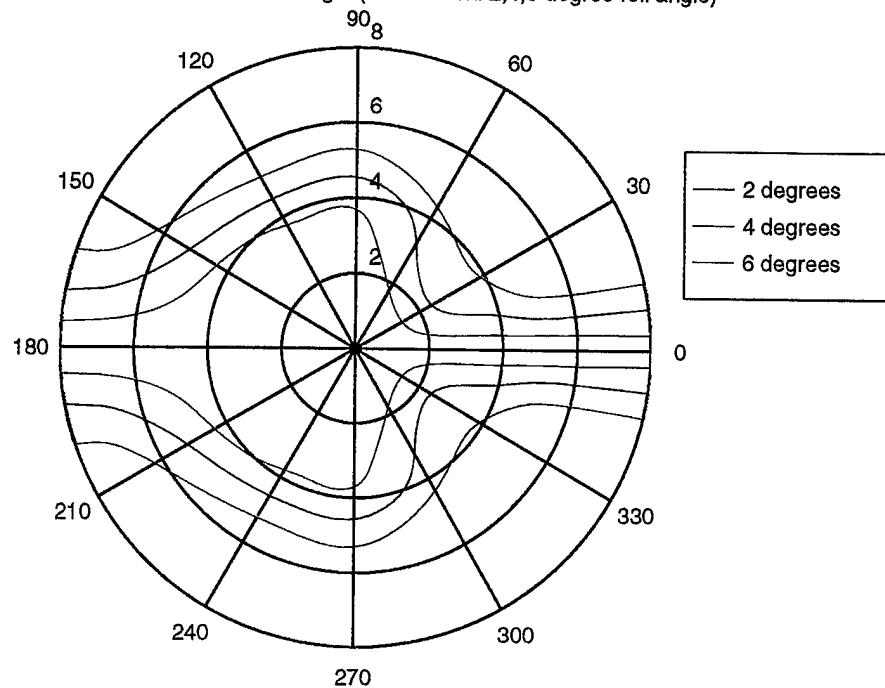


Figure 69. Sea state vs. wave angle for 37.5x1 bilge keel - 6 kts.

Maximum sea state vs. wave angle (for 8 kt. and 2,4,6 degree roll angle)

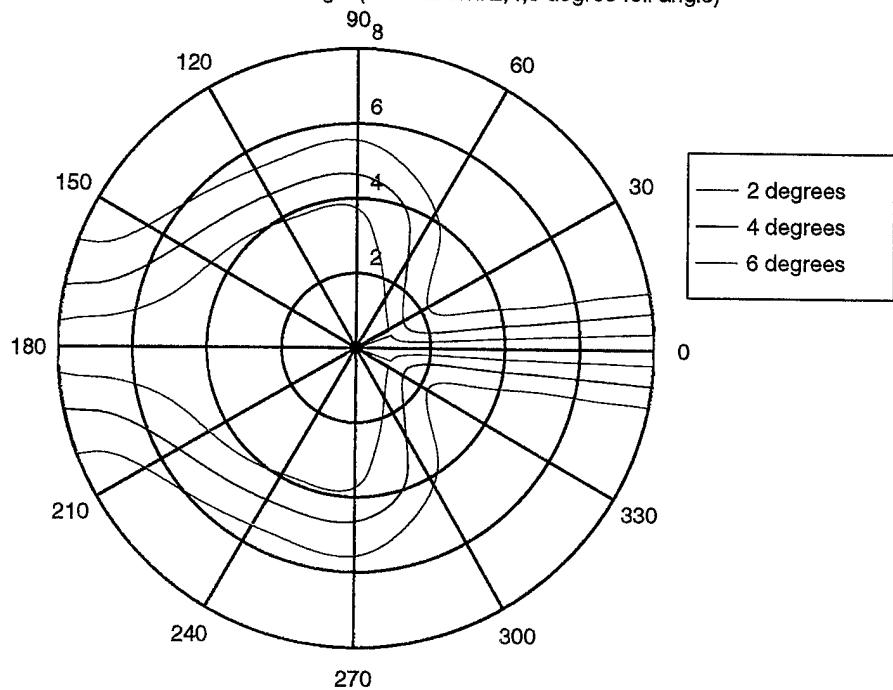


Figure 70. Sea state vs. wave angle for 37.5x1 bilge keel - 8 kts.

Maximum sea state vs. wave angle (for 10 kt. and 2,4,6 degree roll angle)

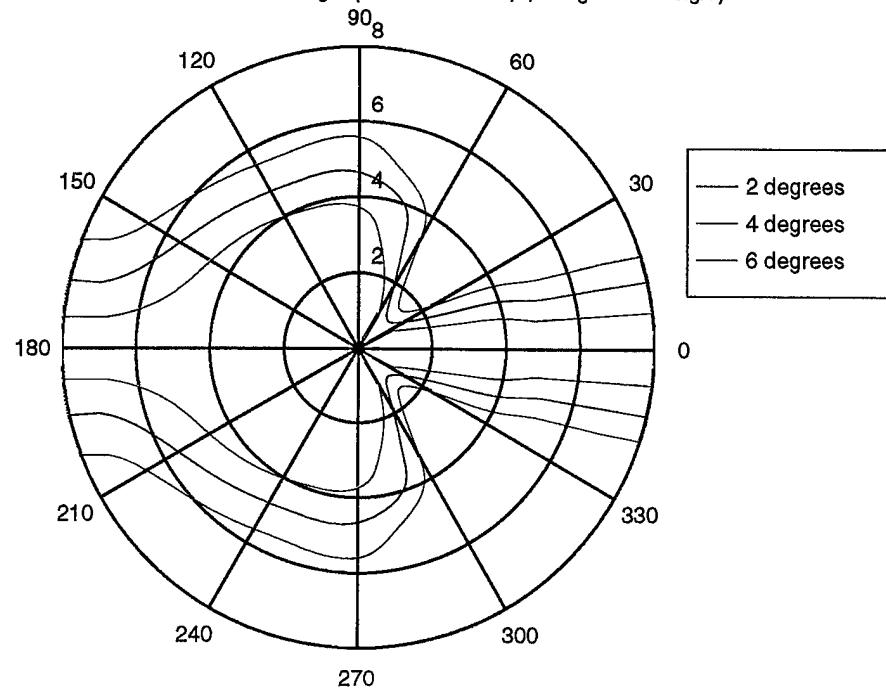


Figure 71. Sea state vs. wave angle for 37.5x1 bilge keel - 10 kts.

Maximum sea state vs. wave angle (for 12 kt. and 2,4,6 degree roll angle)

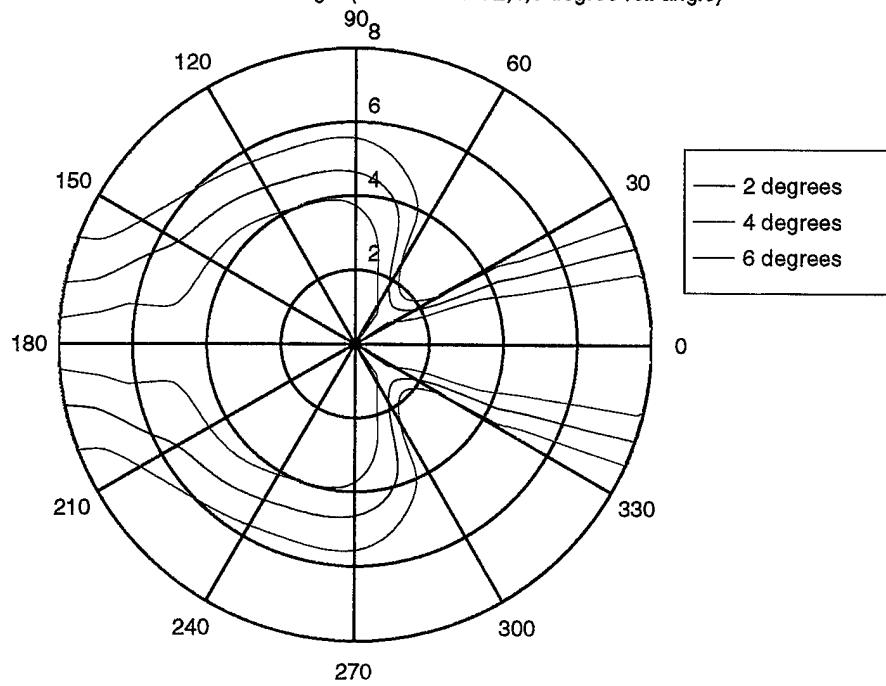


Figure 72. Sea state vs. wave angle for 37.5x1 bilge keel - 12 kts.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

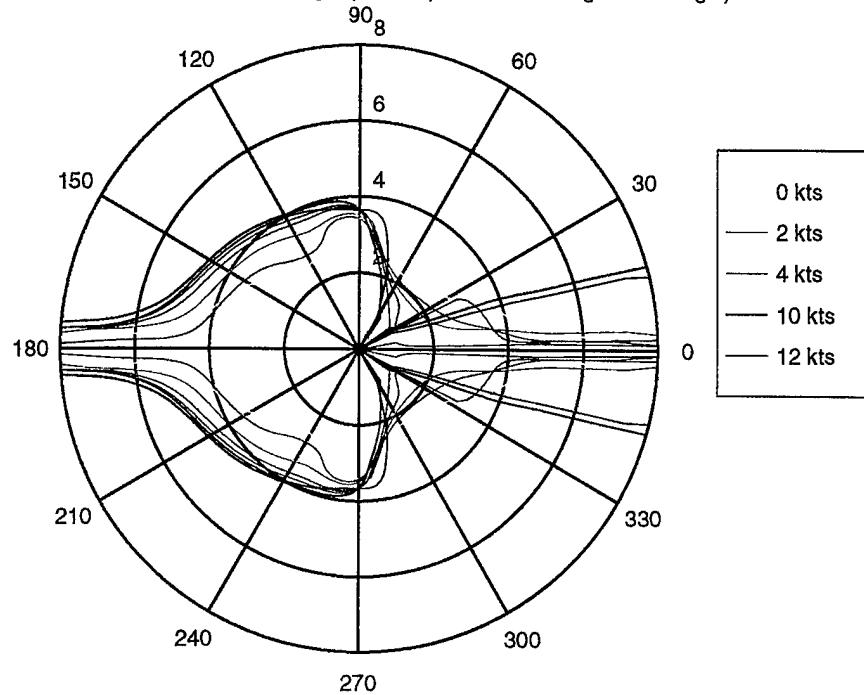


Figure 73. Sea state vs. wave angle, no bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

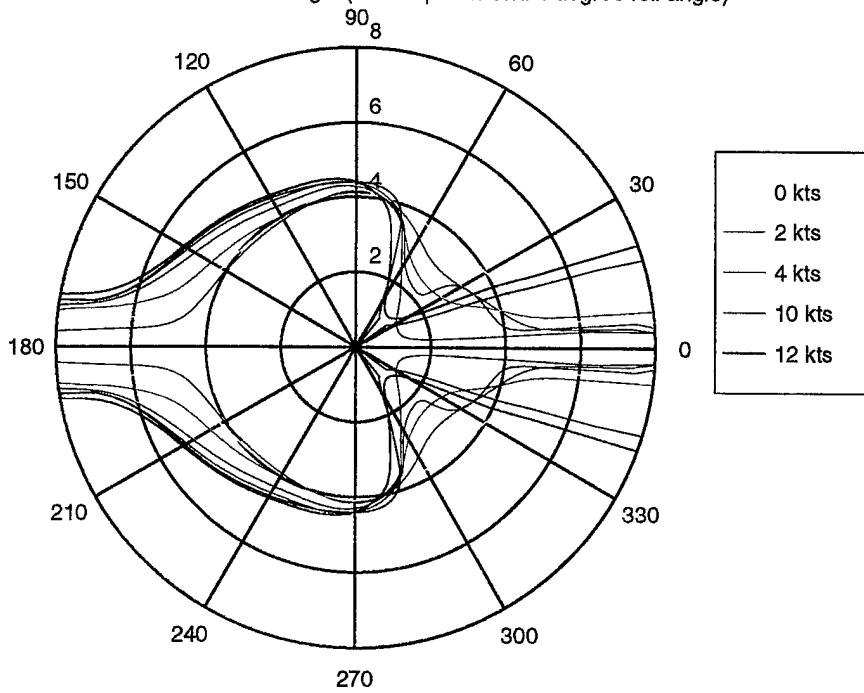


Figure 74. Sea state vs. wave angle, no bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

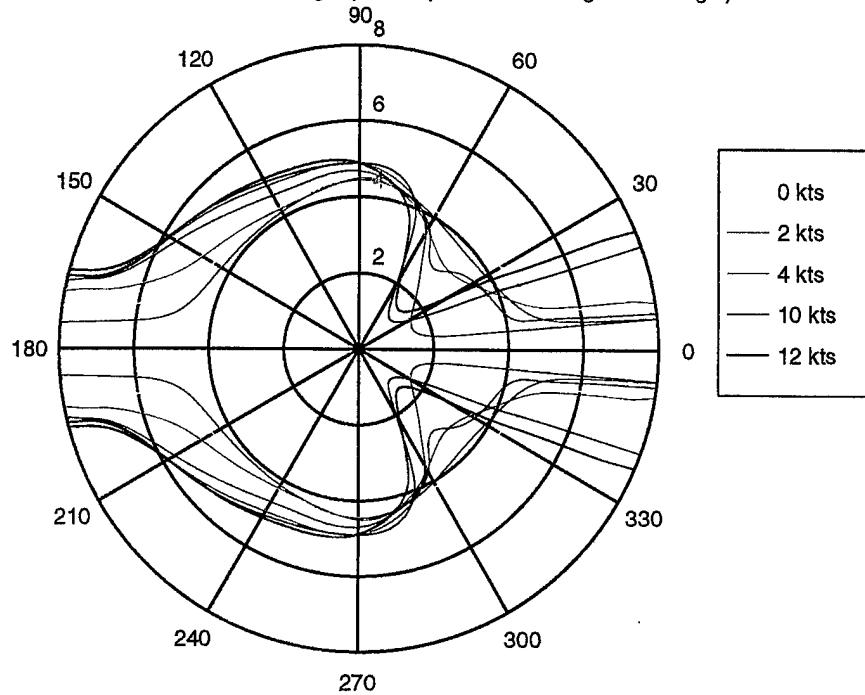


Figure 75. Sea state vs. wave angle, no bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

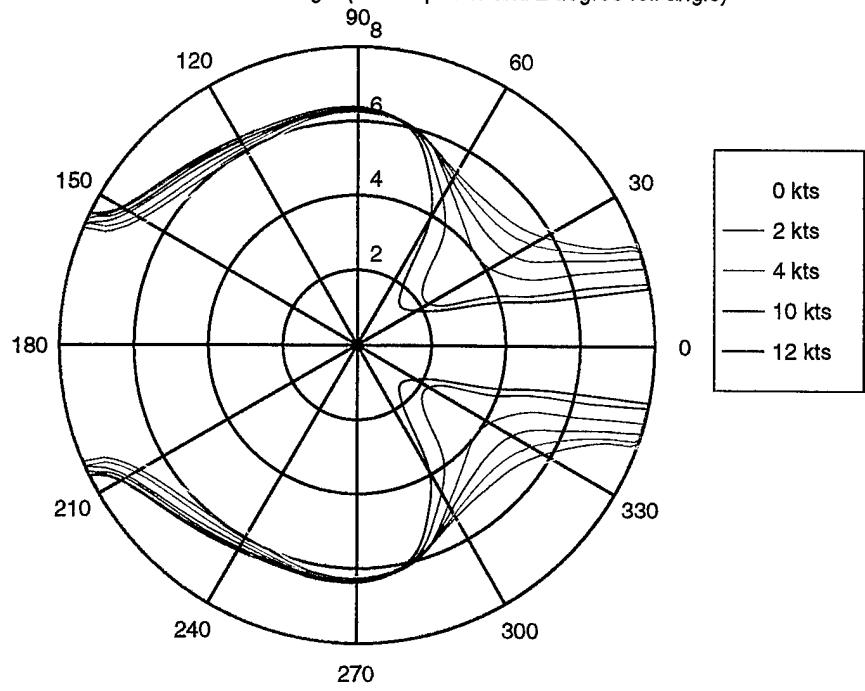


Figure 76. Sea state vs. wave angle, 150x3 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

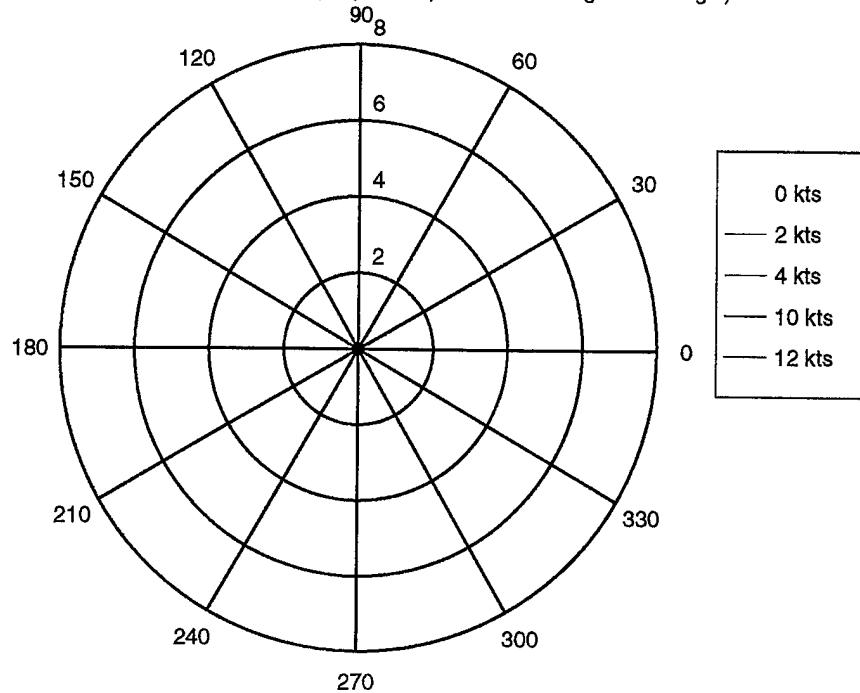


Figure 77. Sea state vs. wave angle, 150x3 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

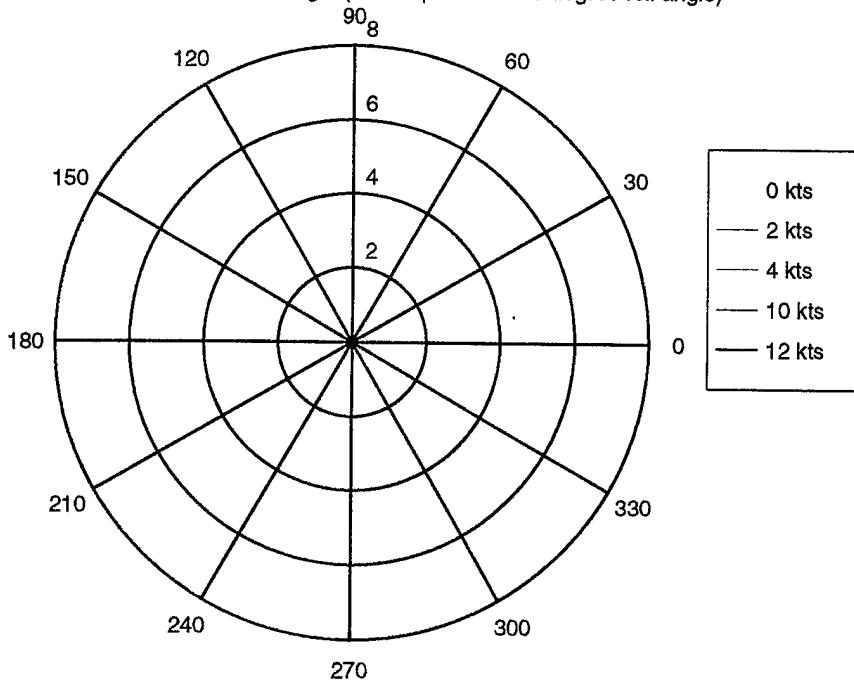


Figure 78. Sea state vs. wave angle, 150x3 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

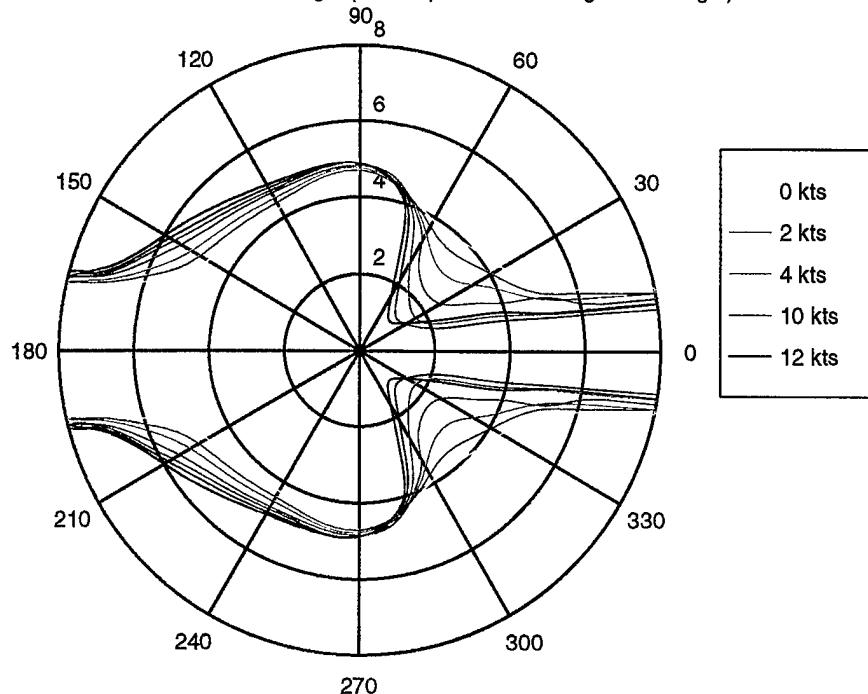


Figure 79. Sea state vs. wave angle, 150x2 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

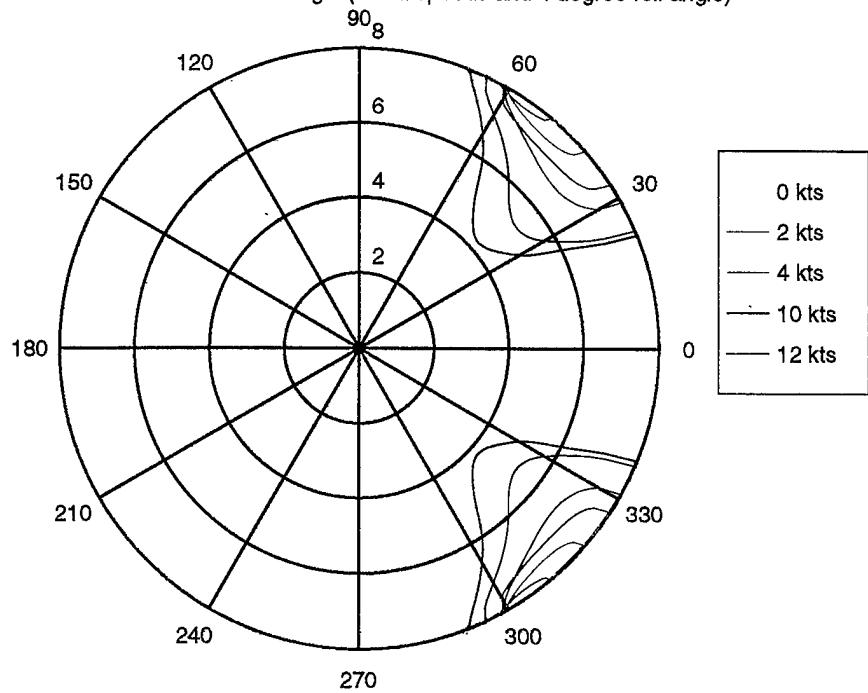


Figure 80. Sea state vs. wave angle, 150x2 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

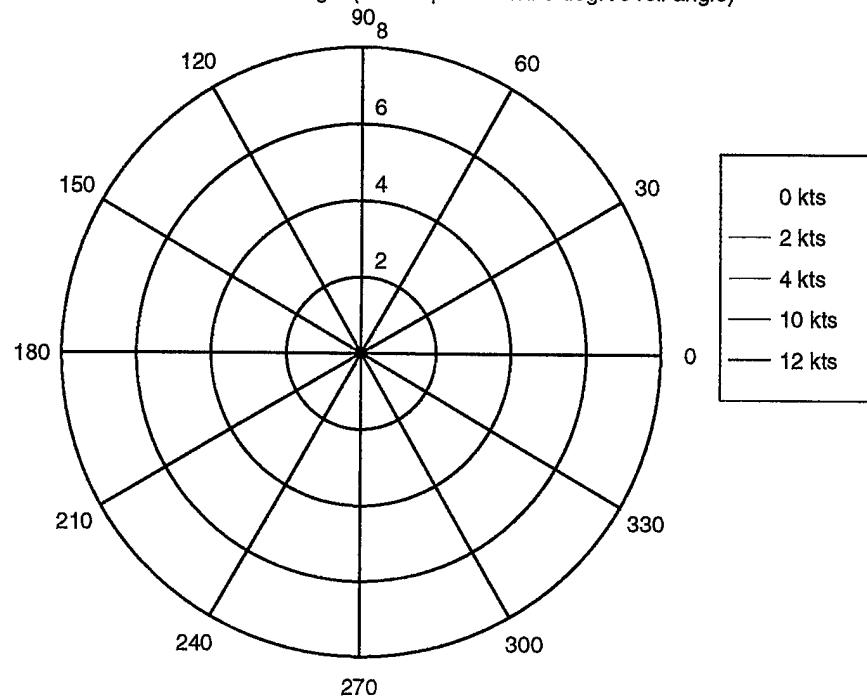


Figure 81. Sea state vs. wave angle, 150x2 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

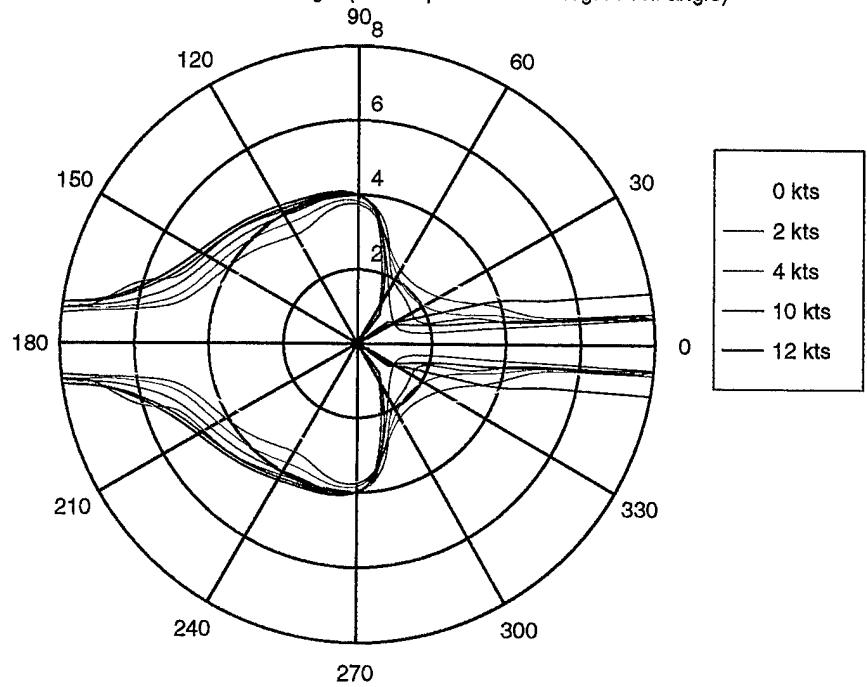


Figure 82. Sea state vs. wave angle, 150x1 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

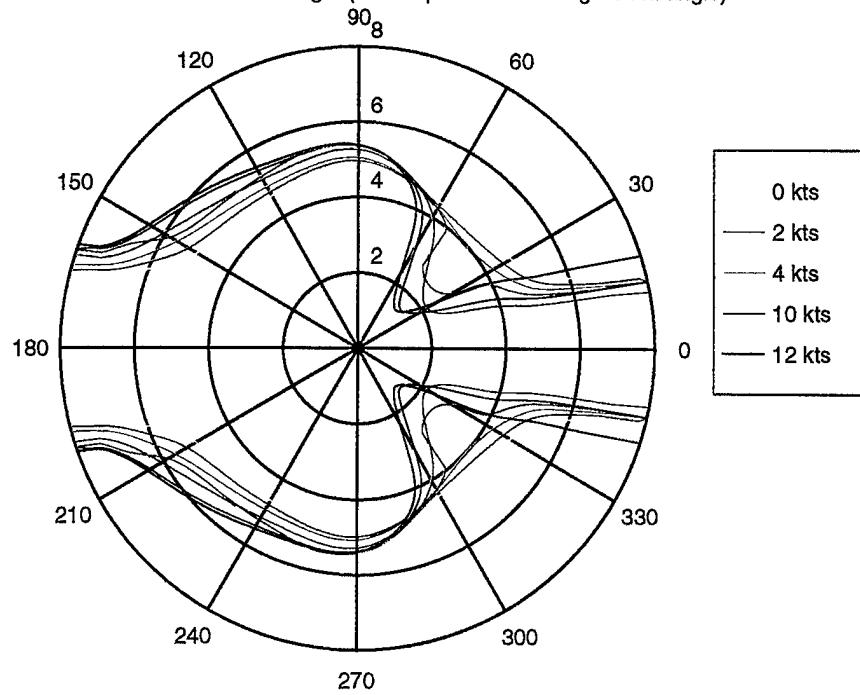


Figure 83. Sea state vs. wave angle, 150x1 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

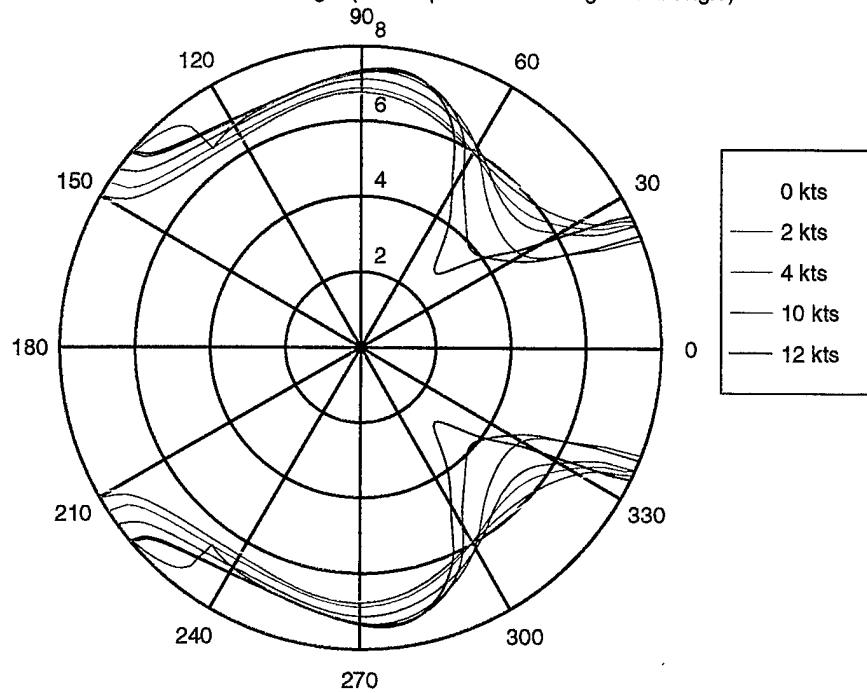


Figure 84. Sea state vs. wave angle, 150x1 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

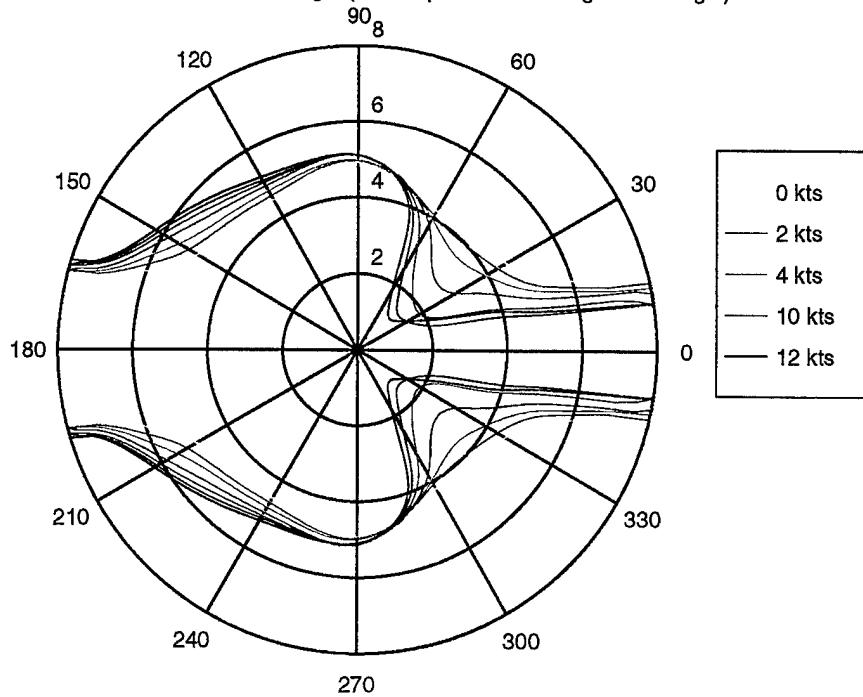


Figure 85. Sea state vs. wave angle, 75x3 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

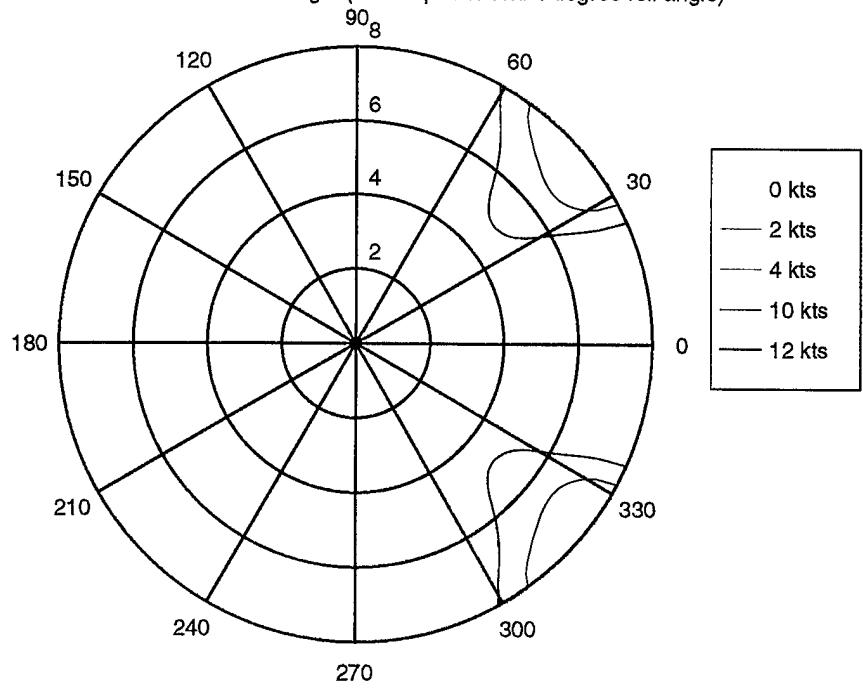


Figure 86. Sea state vs. wave angle, 75x3 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

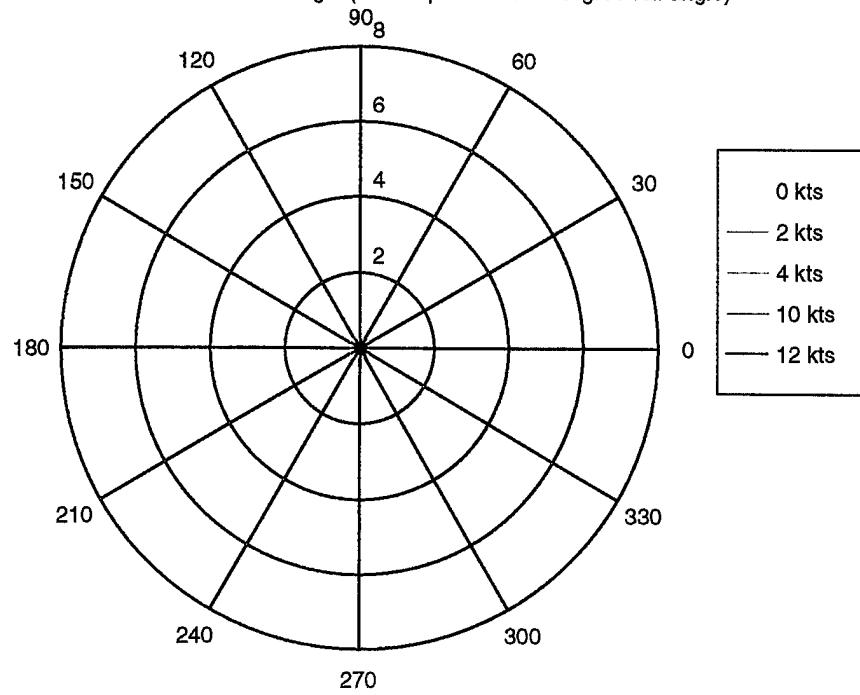


Figure 87. Sea state vs. wave angle, 75x3 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

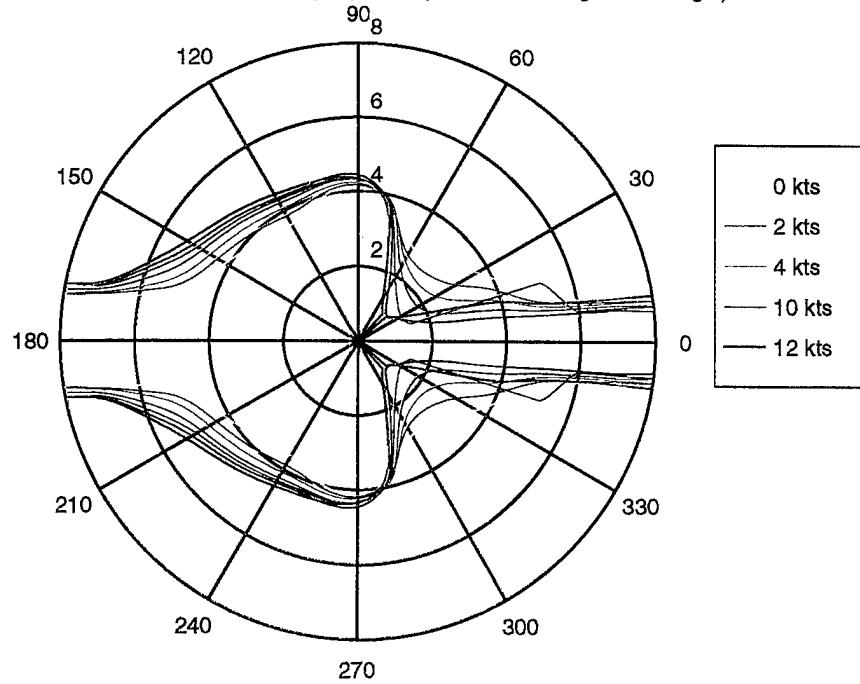


Figure 88. Sea state vs. wave angle, 75x2 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

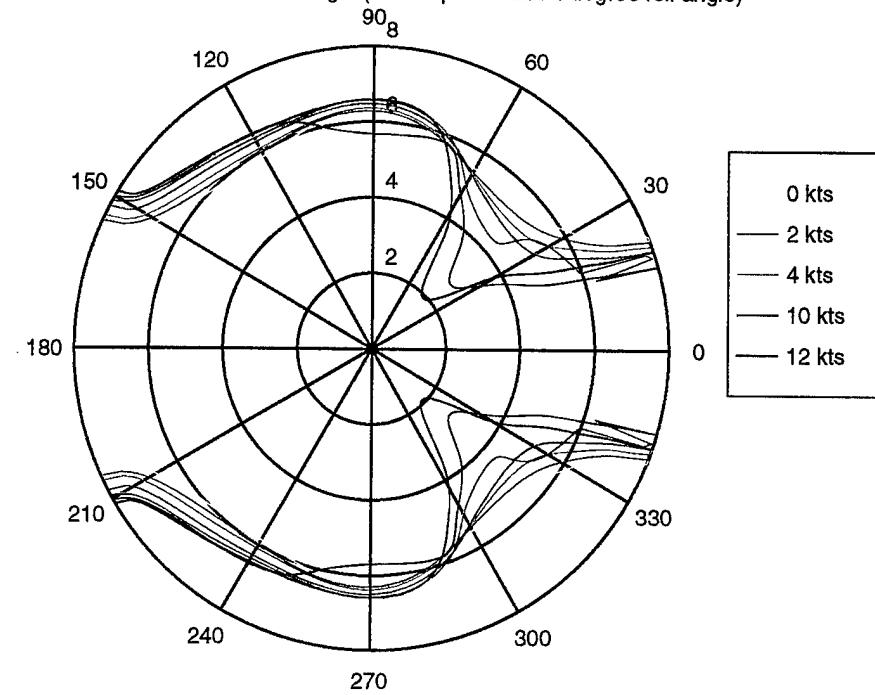


Figure 89. Sea state vs. wave angle, 75x2 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

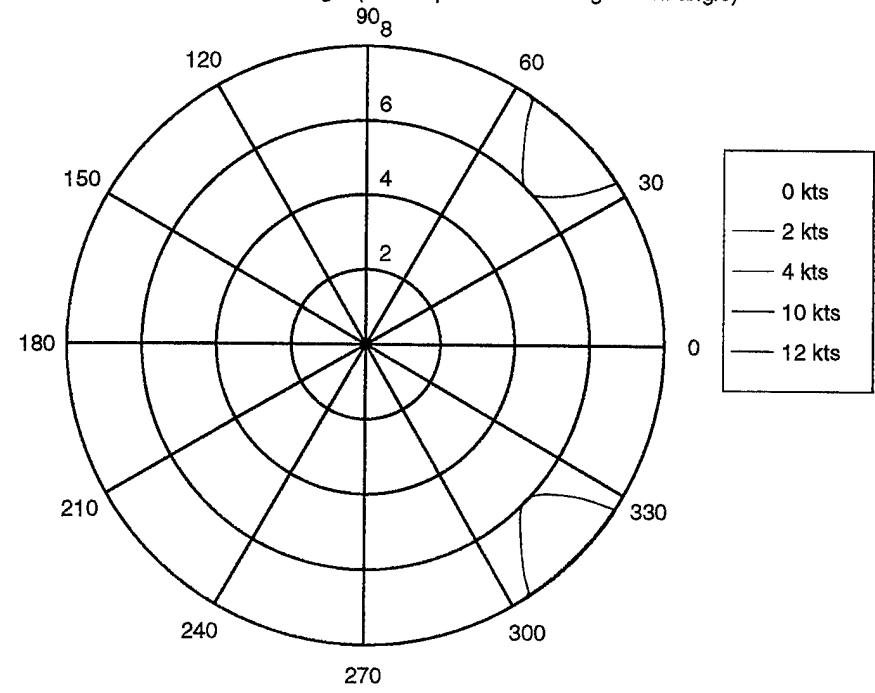


Figure 90. Sea state vs. wave angle, 75x2 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

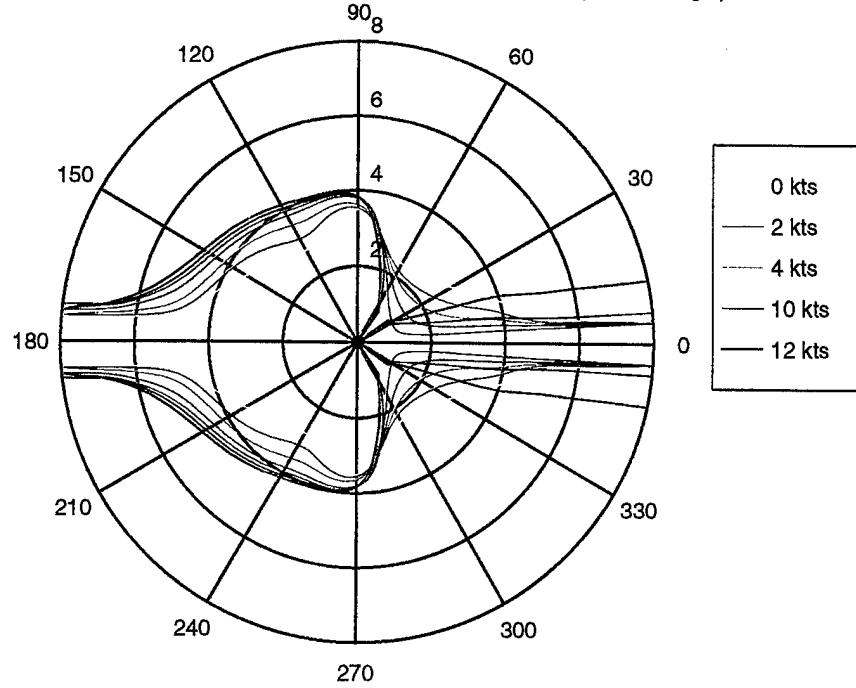


Figure 91. Sea state vs. wave angle, 75x1 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

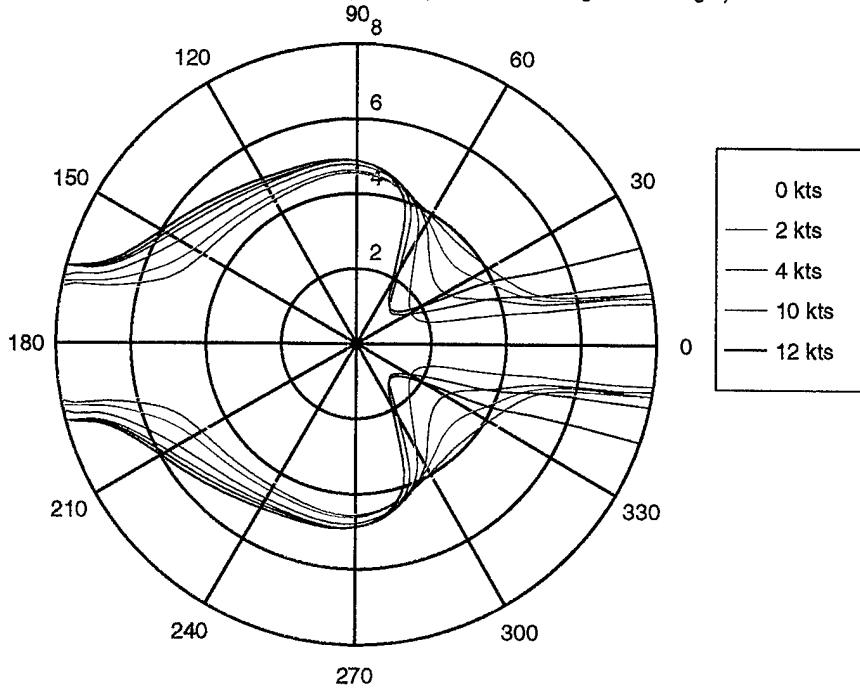


Figure 92. Sea state vs. wave angle, 75x1 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

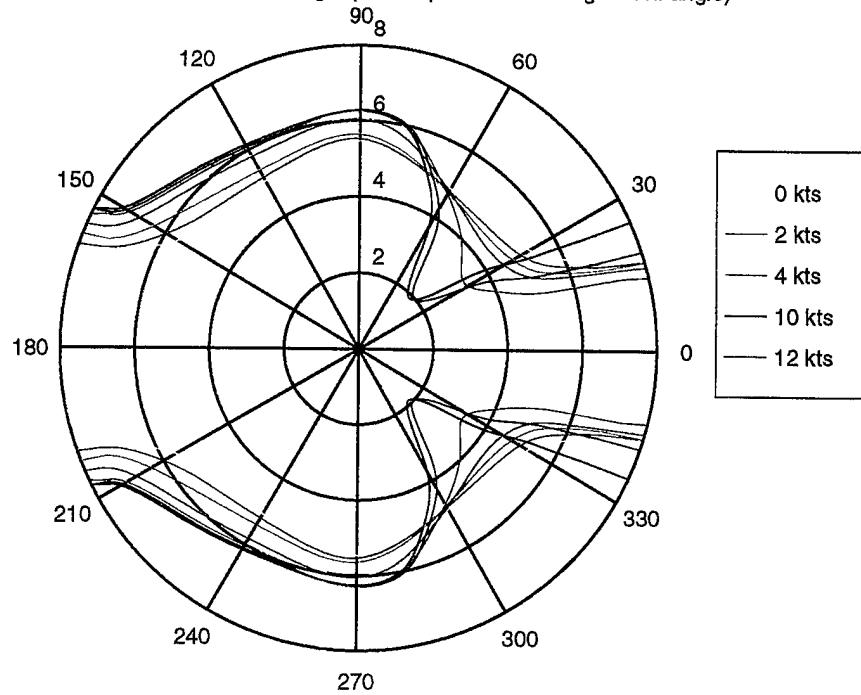


Figure 93. Sea state vs. wave angle, 75x1 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

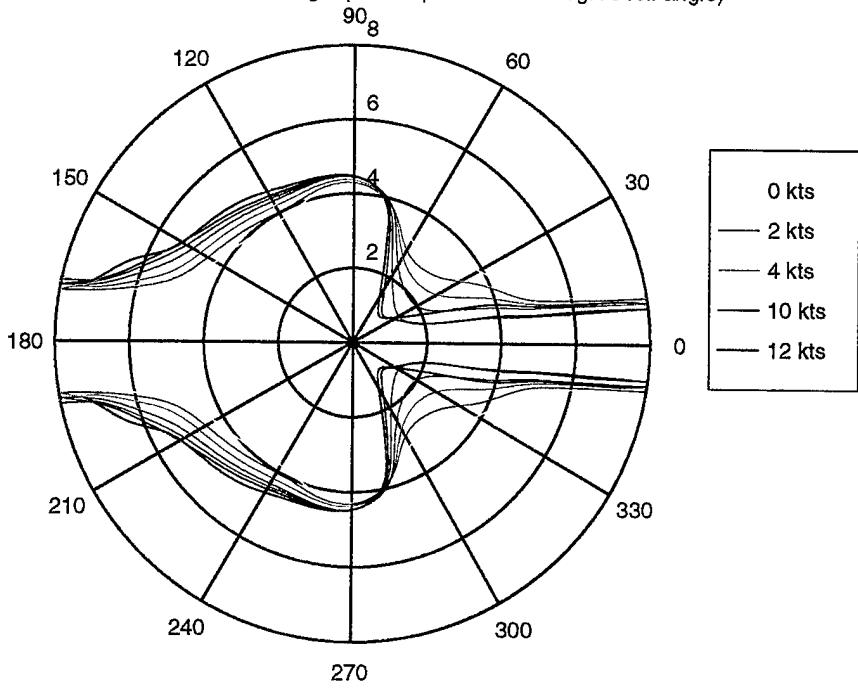


Figure 94. Sea state vs. wave angle, 37.5x3 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

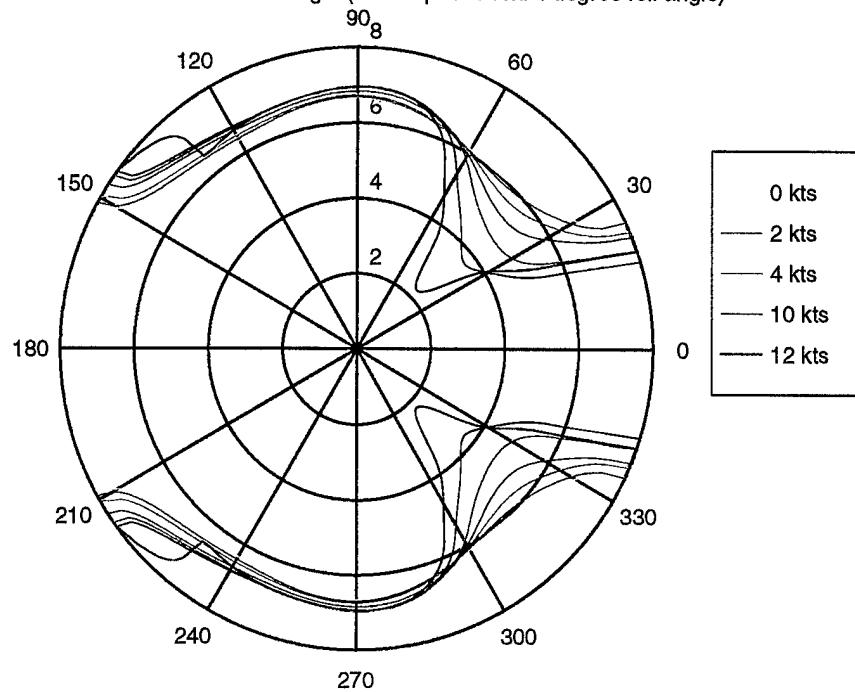


Figure 95. Sea state vs. wave angle, 37.5x3 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

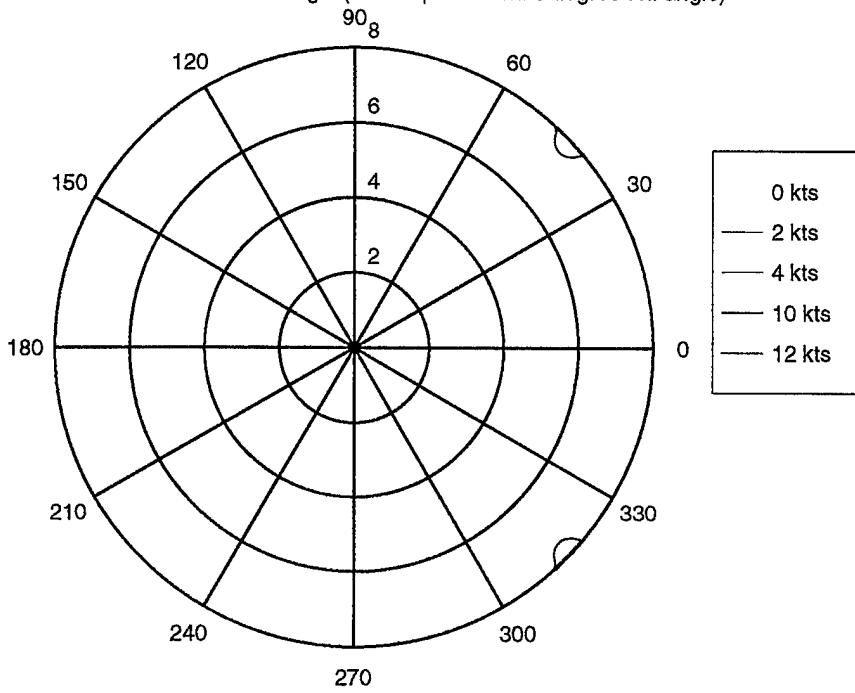


Figure 96. Sea state vs. wave angle, 37.5x3 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

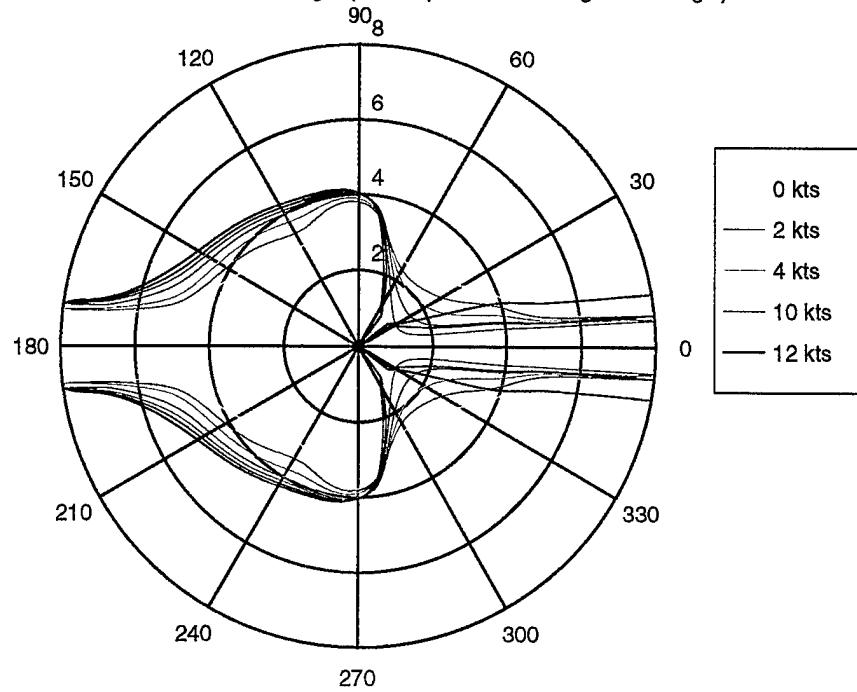


Figure 97. Sea state vs. wave angle, 37.5x2 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

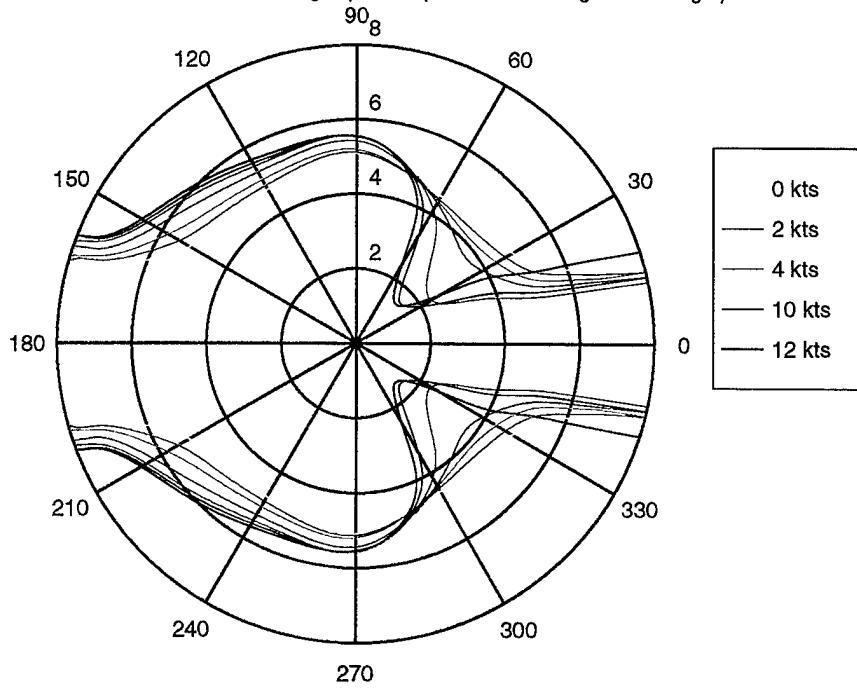


Figure 98. Sea state vs. wave angle, 37.5x2 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

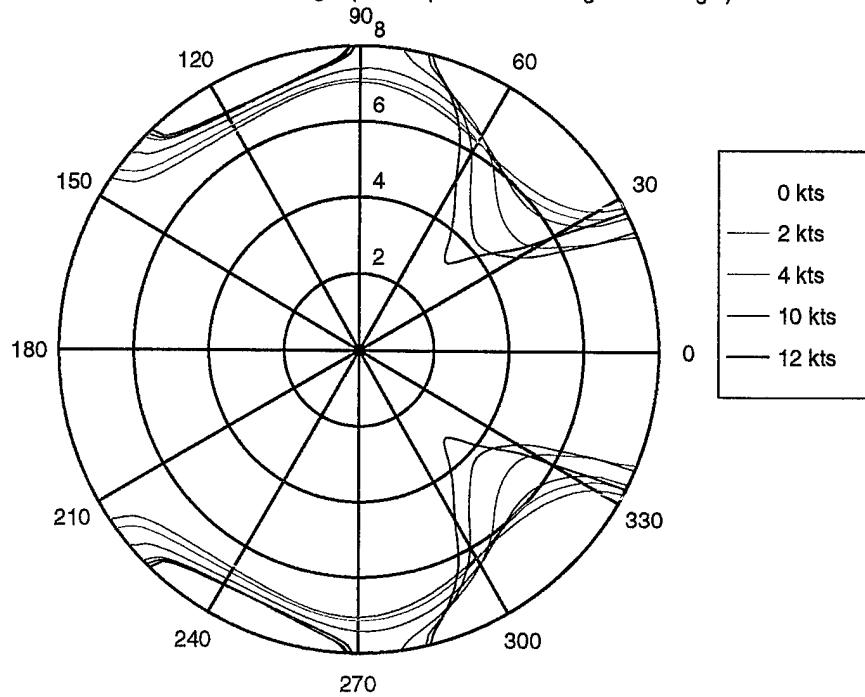


Figure 99. Sea state vs. wave angle, 37.5x2 bilge keel, 6 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 2 degree roll angle)

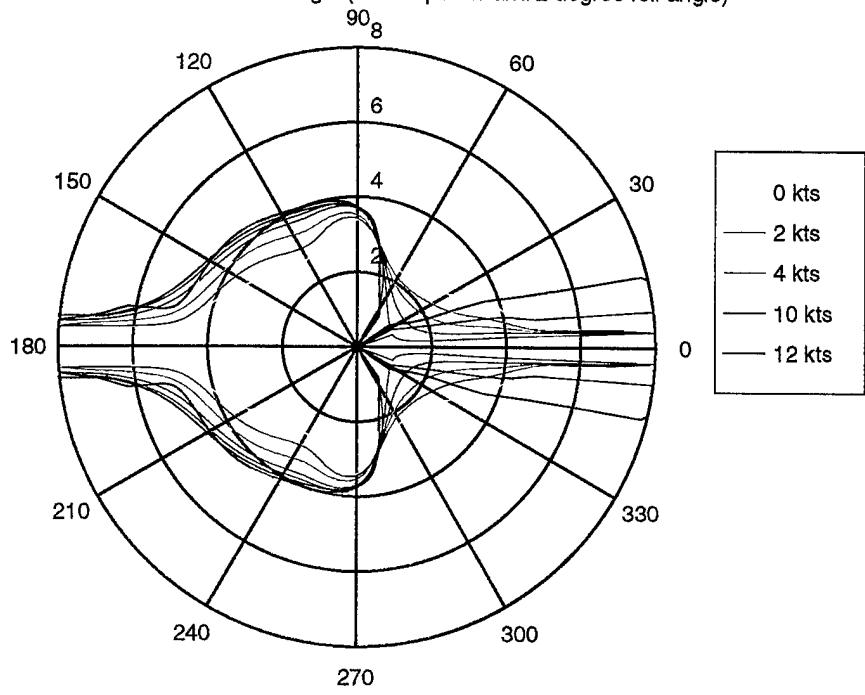


Figure 100. Sea state vs. wave angle, 37.5x1 bilge keel, 2 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 4 degree roll angle)

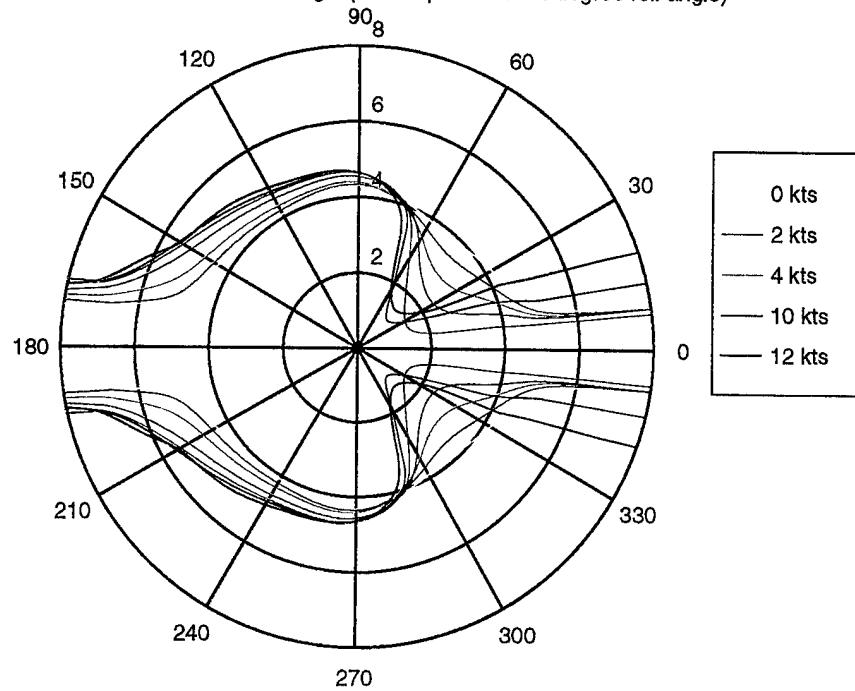


Figure 101. Sea state vs. wave angle, 37.5x1 bilge keel, 4 degrees roll.

Maximum sea state vs. wave angle (for all speeds and 6 degree roll angle)

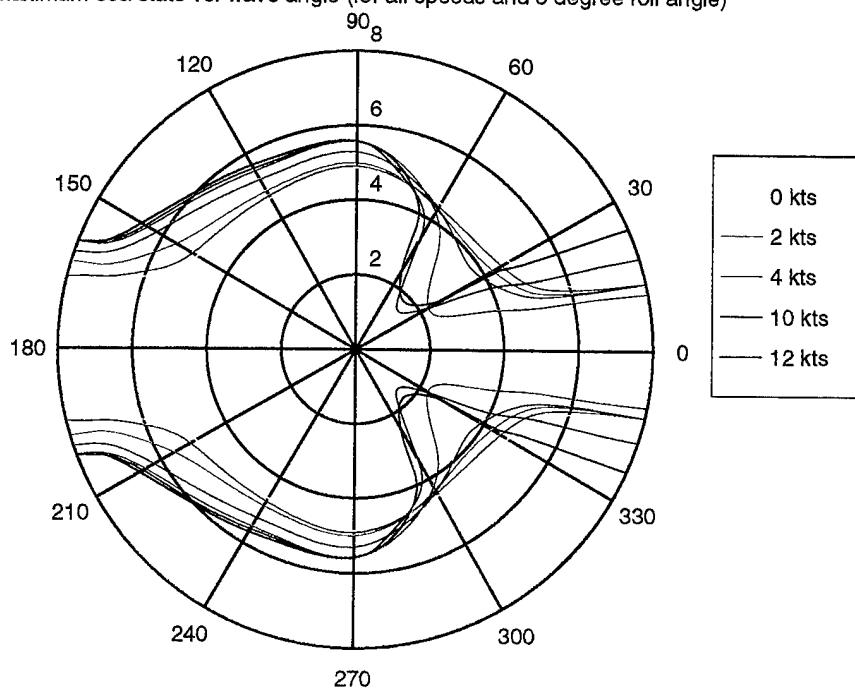


Figure 102. Sea state vs. wave angle, 37.5x1 bilge keel, 6 degrees roll.

## **B. OPERABILITY INDICES**

Operability Indices, as used in this study, can provide a relative measure of the ship's ability to operate under all sea states and speeds. From the polar plot for each speed and a given maximum roll angle, the area encircled by the resulting curve could be calculated utilizing the trapezoidal method by the use of the trapz function in MATLAB. Similarly, the maximum area of the circle can also be calculated if the ship is assumed to be able to operate in all sea states without exceeding the maximum allowed roll angle. The operability index can then be calculated by dividing the calculated area of interest by the maximum area. Appendix D provides the program used to calculate the operability indices.

By comparing the operability index related to a particular bilge keel size and ship's speed to that of no bilge keel, a relative measure of the effectiveness of that particular bilge keel can be determined. Figure 103 is a plot of the Operability indices for various ship's speeds, no bilge keel, and 2, 4, and 6 degree maximum roll angles. Since one objective of this study was to determine the effectiveness of various bilge keels on the roll characteristics of the ship, a better measure of the effectiveness was found by presenting all bilge keel operability indices with respect to the no bilge keel operability indices. In other words, the operability indices

of the bilge keel under consideration were divided by the respective operability indices for the ship with no bilge keel. If the two values were exactly the same, the result would be 1.0. By multiplying the result with the corresponding no bilge keel operability index value, one could determine the actual respective operability index value. Figures 104 to 112 are plots of these relative values for the range of ship's speed.

Further examination of the operability indices provided some useful points. First, the operability indices seem lowest at 2 and 8 knots for the no bilge keel ship with the absolute minimum at 8 knots. Six knots and speeds above ten knots provide the speeds best suited to allow the ship the highest amount of operability. This results in the bilge keels having less of an effect at these speeds and the greatest effect at 2 and 8 knots. As can be seen, any bilge keel arrangement still significantly improves the operability of the ship at most any ship speed. It appears that shortening the length of the bilge keel by half while maintaining the same width reduces the effectiveness by about 0.2. If the length is maintained constant while the width is reduced in size by one foot, the overall reduction in effectiveness appears to be approximately 0.2 also. These observations are generalities and can vary by a greater or less extent based on the different bilge keels and roll angles examined.

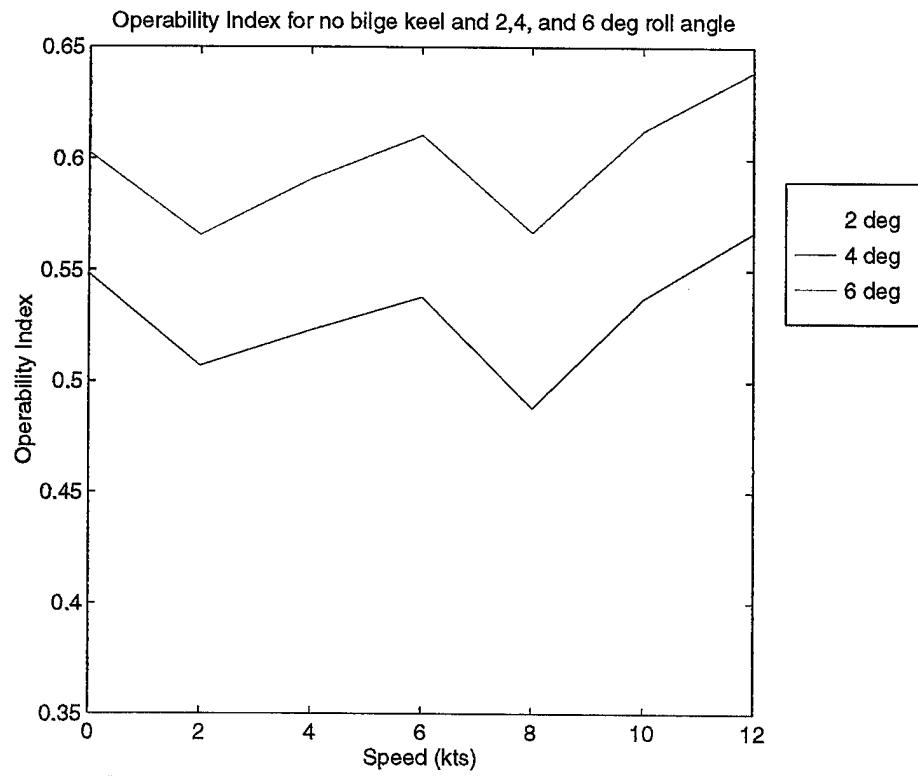


Figure 103. Operability Index for no bilge keel.

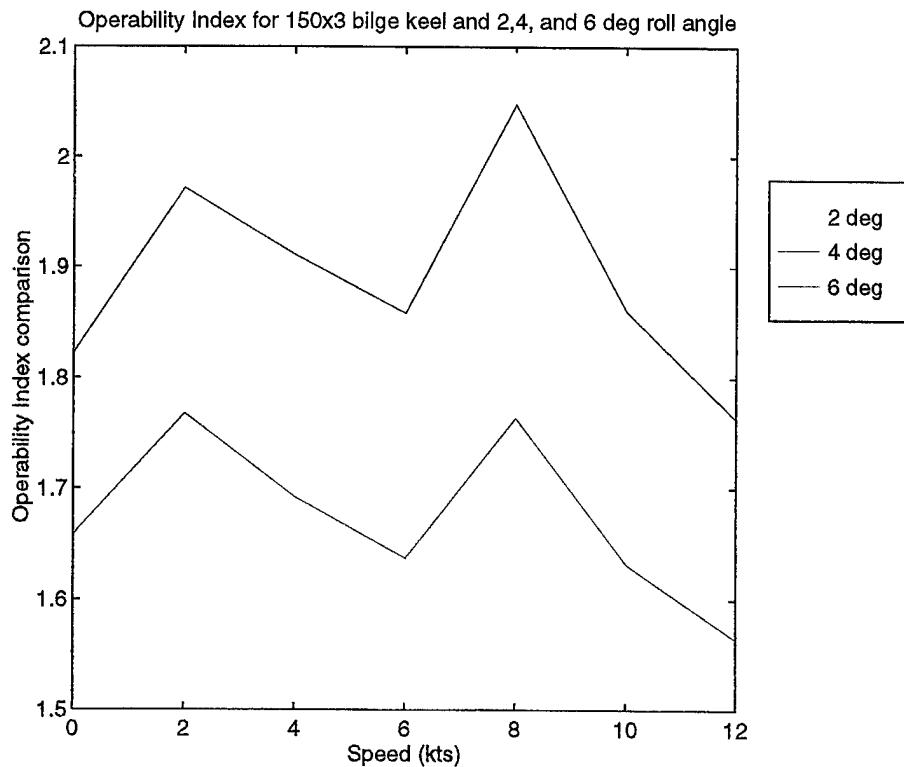


Figure 104. Operability Index for 150x3 bilge keel.

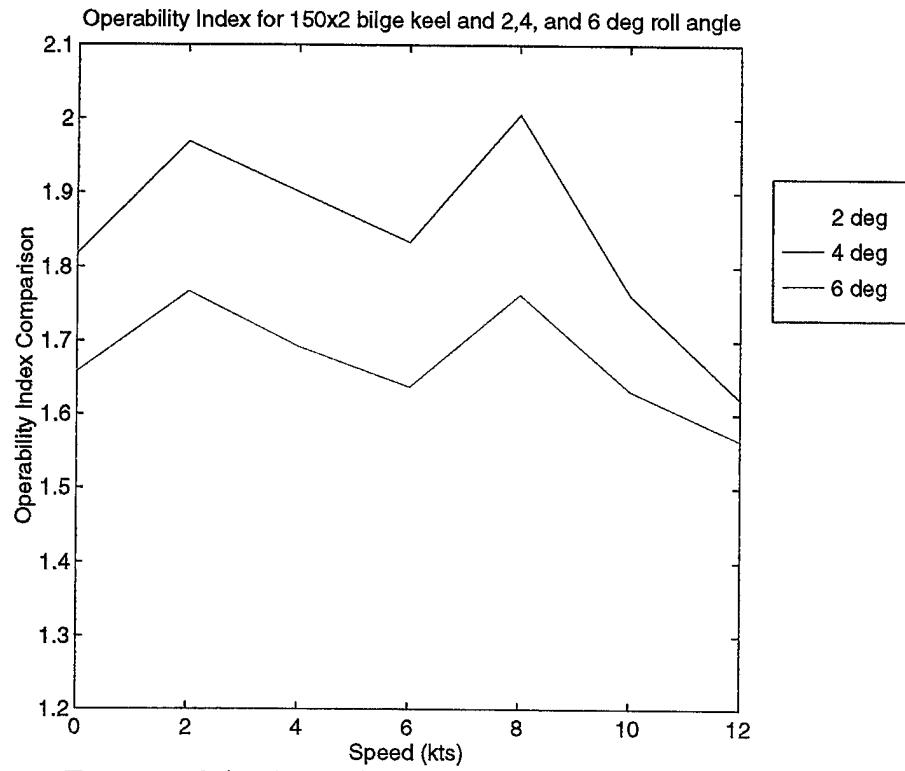


Figure 105. Operability Index for 150x2 bilge keel.

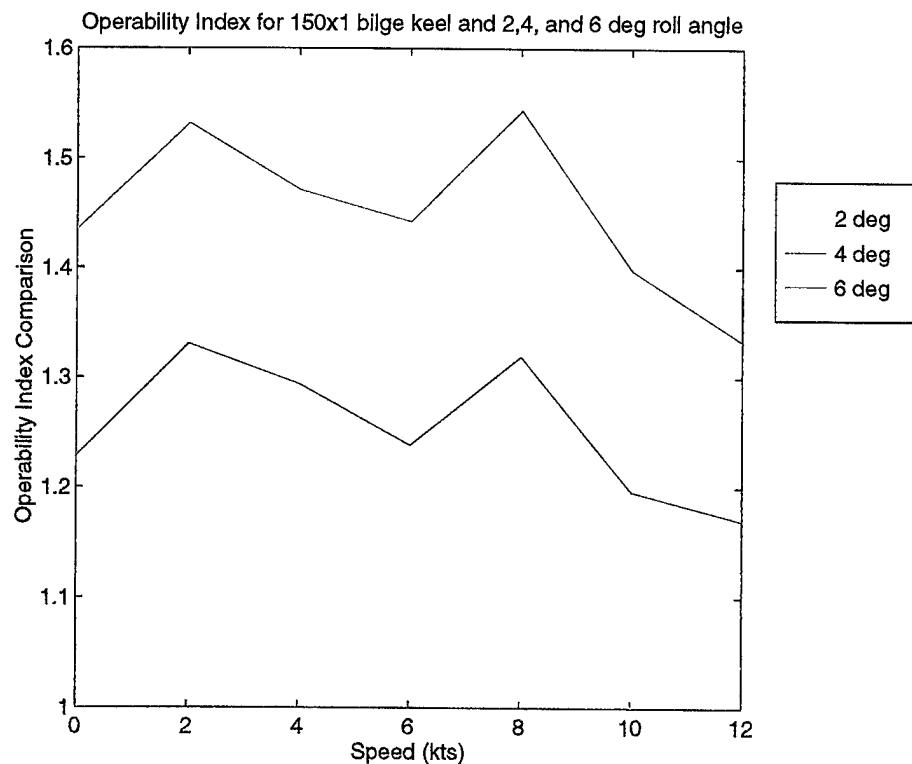


Figure 106. Operability Index for 150x1 bilge keel.

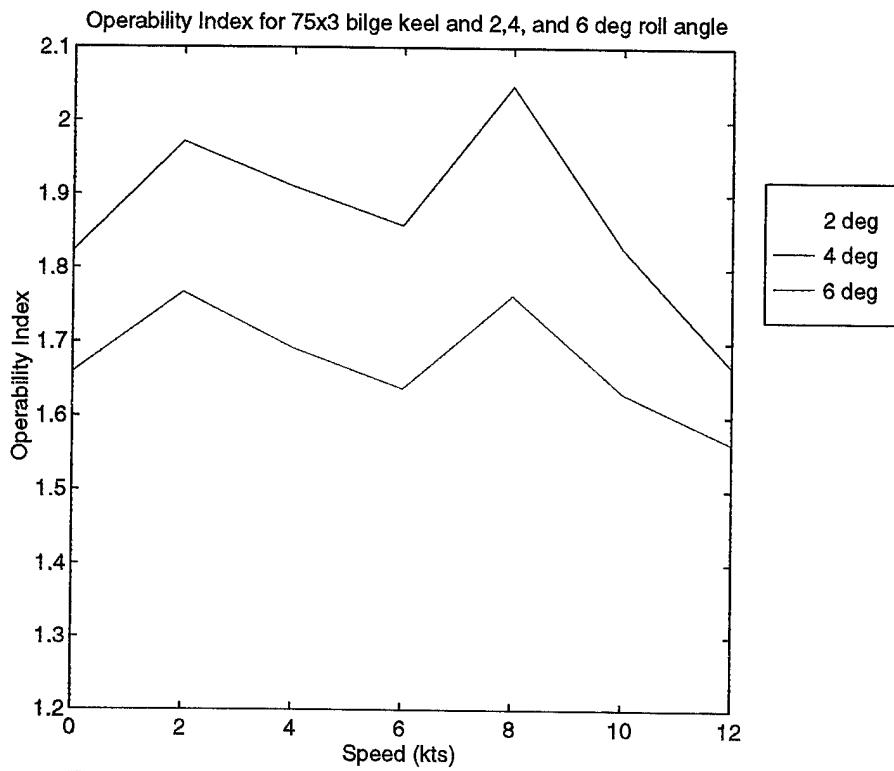


Figure 107. Operability Index for 75x3 bilge keel.

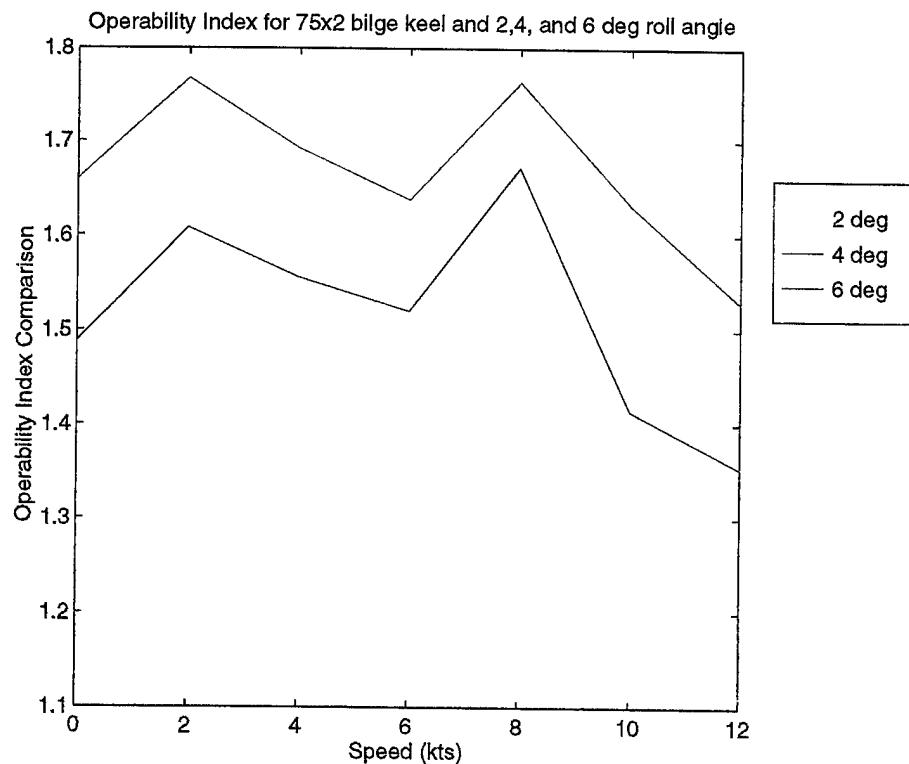


Figure 108. Operability Index for 75x2 bilge keel.

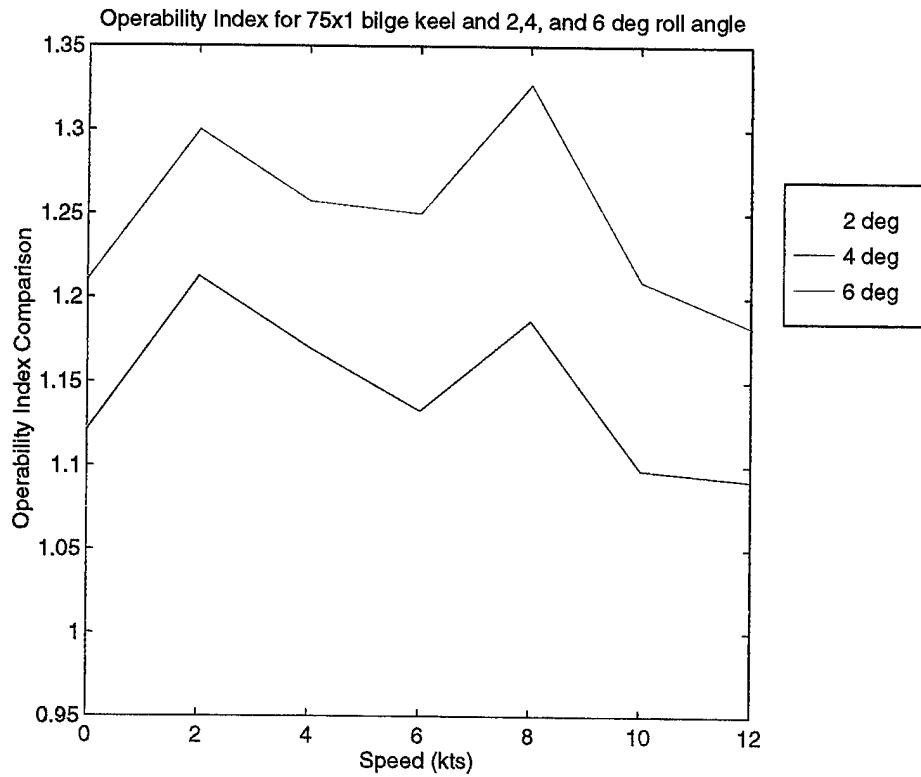


Figure 109. Operability Index for 75x1 bilge keel.

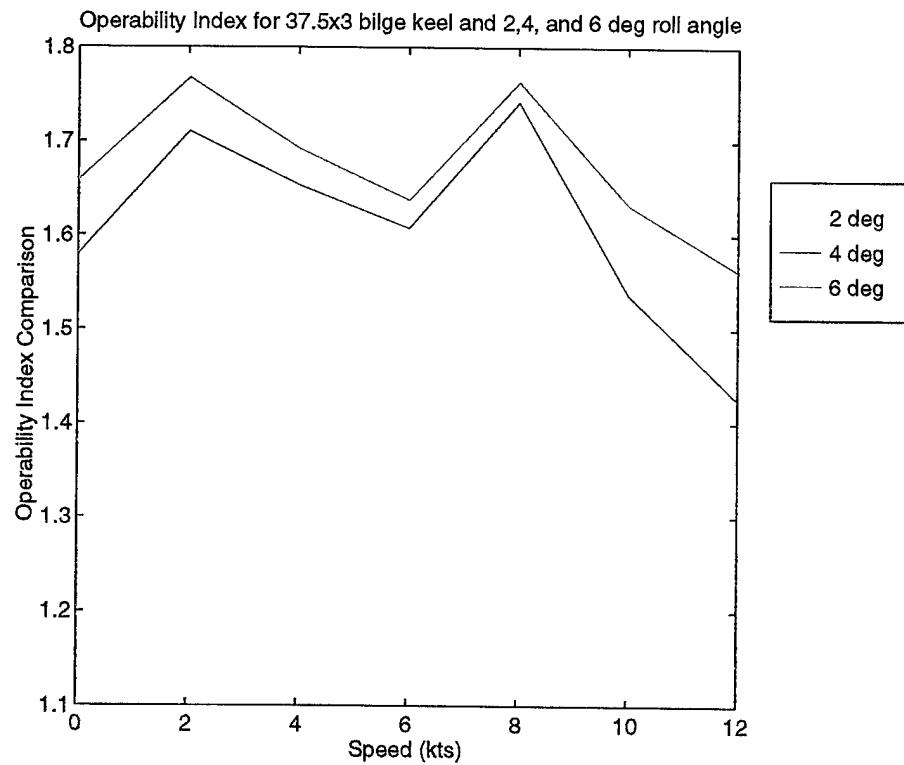


Figure 110. Operability Index for 37.5x3 bilge keel.

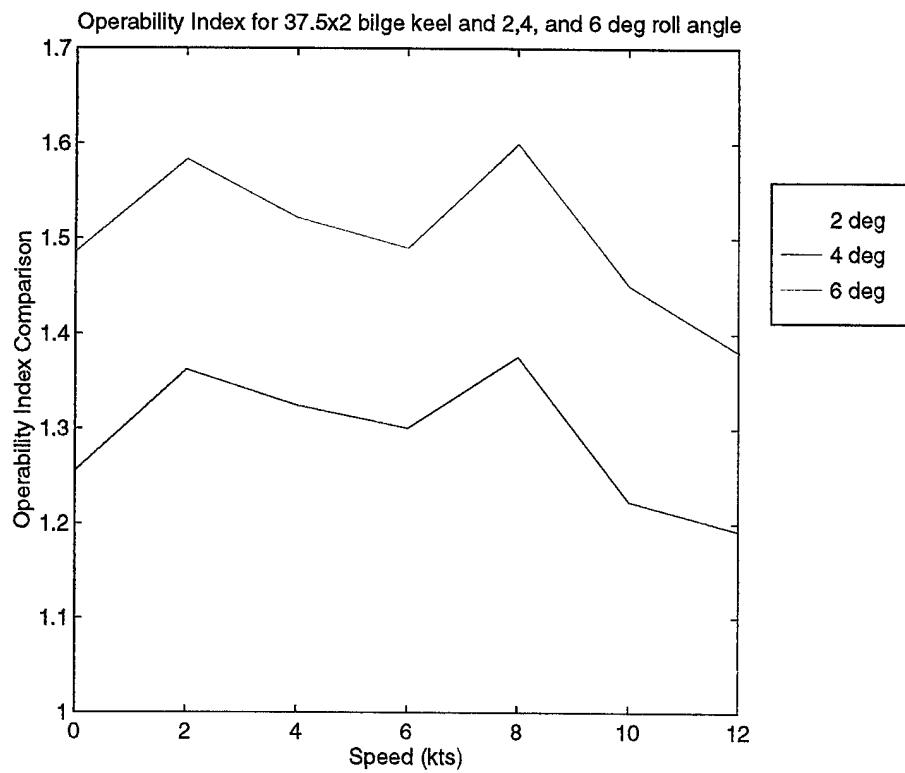


Figure 111. Operability Index for 37.5x2 bilge keel.

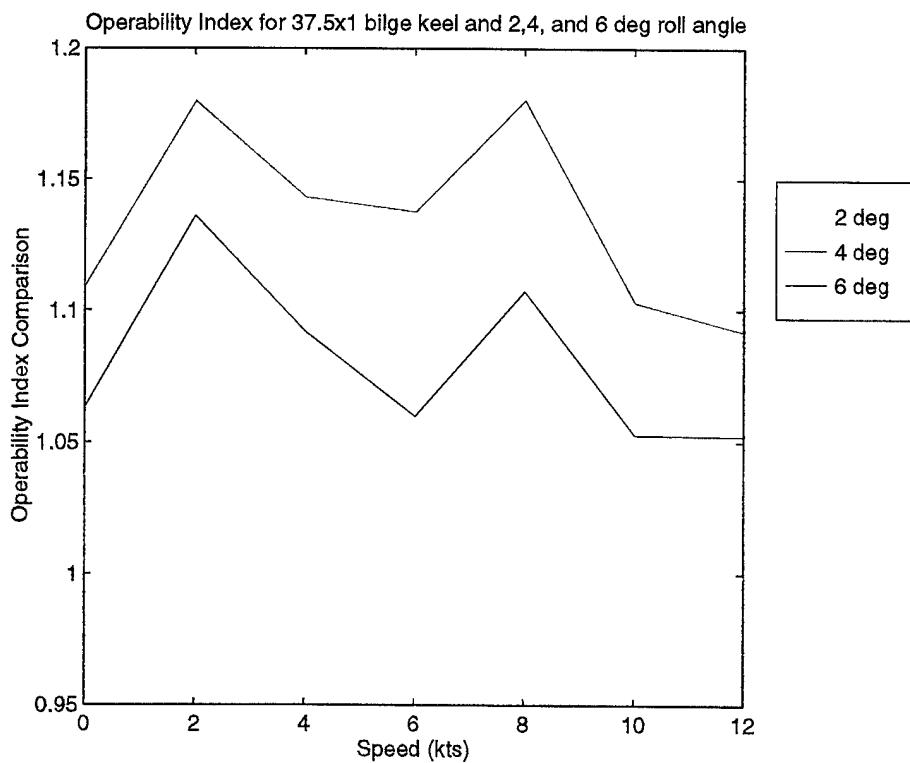


Figure 112. Operability Index for 37.5x1 bilge keel.

## **IV. CONCLUSIONS AND RECOMMENDATIONS**

### **A. CONCLUSIONS**

As was seen, not only the size of a wave incident to a ship but also the ship's speed can produce large roll effects. Wave direction also played a large part on the magnitude of the ship's roll. The data provided favorable results regarding the use of bilge keels to reduce the magnitude of the ship's roll. These results, though, are based on theory and historical results. So, the possibility exists that actual bilge keel performance could and probably will vary from the results found in this study. The following conclusions can be drawn:

1. As was expected, the maximum allowed sea state increased as the maximum allowed roll angle was increased.
2. As ship's speed was increased, the maximum allowed sea state correspondingly decreased.
3. Beam seas seemed to have a significant effect on the roll characteristics of the ship and roll was zero for sea directions relating to the bow or stern of the ship. The largest effect, however, on roll angle came from quartering seas with quartering seas aft the beam having the

largest effect. Thus, aft quartering seas being the limiting position for roll angle limits.

4. Significant roll dampening can be applied by the use of bilge keels.
5. The operability indices seem lowest at 2 and 8 knots for the no bilge keel ship with the absolute minimum at 8 knots. Thus, bilge keels will have the greatest effect at these speeds.
6. Any bilge keel arrangement can significantly improve the operability of the ship.
7. Speeds below six knots and above ten knots provided the ship the highest amount of operability with no bilge keel. Bilge keels still proved to significantly decrease the roll motion of the ship even at these speeds.
8. Shortening the length of the bilge keel by half while maintaining the same width appeared to reduce the effectiveness by approximately 0.2.
9. If the bilge keel length is maintained constant while the width is reduced in size by one foot, the overall reduction in effectiveness appears to be approximately 0.2 also.

## **B. RECOMMENDATIONS**

To continue the research on this topic, the following recommendations are made:

1. This study investigated the effects of bilge keels on the roll characteristics of the ship. Several other methods of providing roll dampening exist and could also be explored.
2. Once the placement of the radar masts, or other equipment of concern, have been determined, motion characteristics at these locations could be determined. These motions would result not only because of roll but also because of the other modes of motion of the ship.
3. Once the maximum allowable roll angle for proper operation of the masts and/or equipment of concern has been determined, the minimum required bilge keel size can then be determined by the same methods of this study.



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12. Military Sealift Command Body Plans for T-AGOS class 4 Ship, USS TRIUMPH, Plan Number 801-0000001.
13. MATLAB by The Mathworks, INC. , 1984-1994.



## APPENDIX A. SAMPLE SHIPMO DATA INPUT FILE.

Initial for T-agos

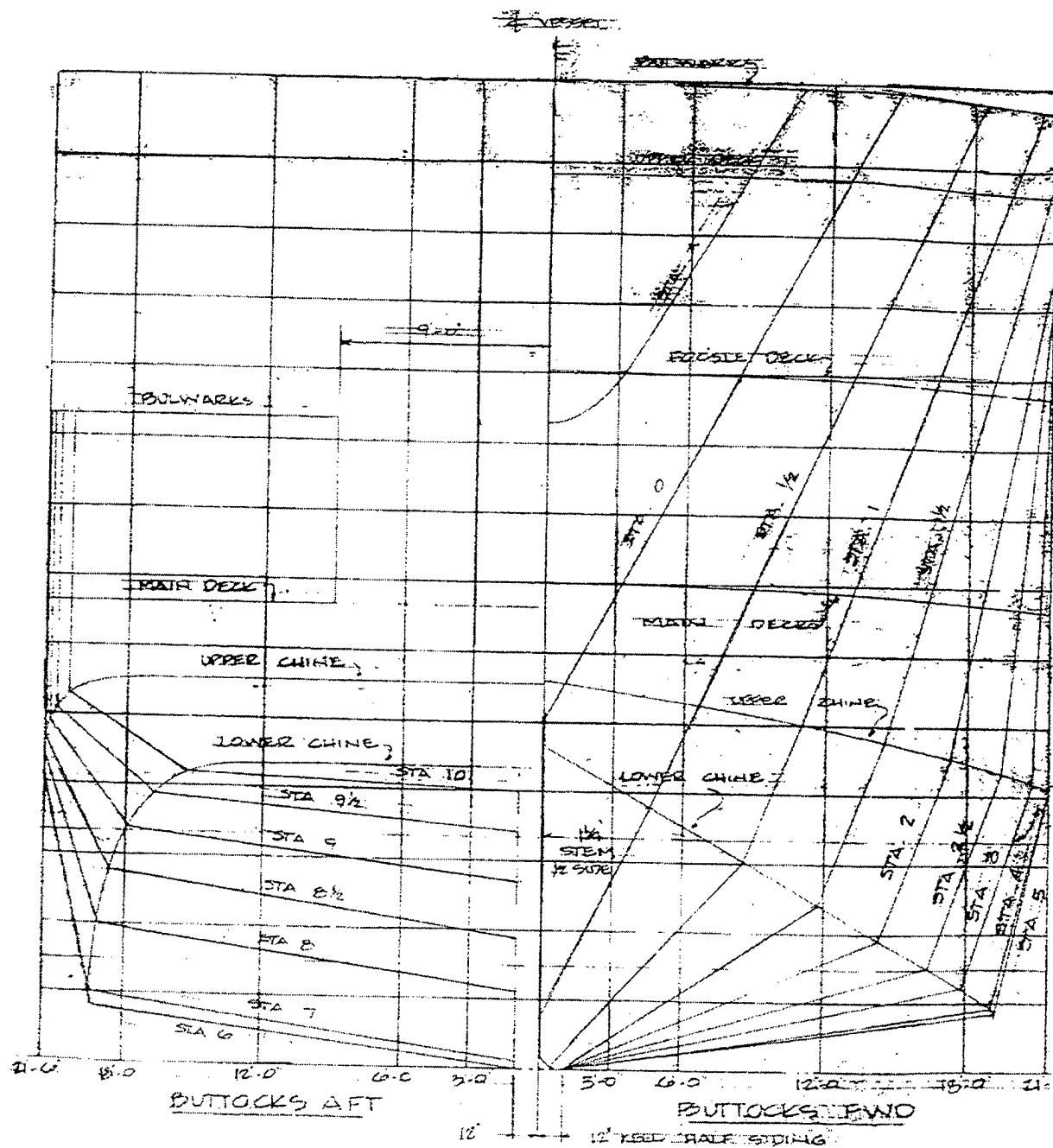
0	0	1	2	1	0	1	1	0	0	1	0	0	17	0
224.00	30.00	3.00	3.00	22.96	5.28	12.00								
224.0000	1.9905	32.1740	0.00000E+00	0.00000E+00	0.0000									
18.7500	-18.7500	1.0000												
1	97.0000	0.0000	0											
0.0000	-15.0000													
6	87.3000	0.0000	0											
0.0000	-15.0000													
0.5208	-12.0000													
1.8750	-9.0000													
3.0458	-6.0000													
5.0000	-3.0000													
6.5000	0.0000													
6	77.6000	0.0000	0											
0.0000	-15.0000													
3.1563	-12.0000													
5.8125	-9.0000													
8.5417	-6.0000													
9.9375	-3.0000													
10.9790	0.0000													
6	67.9000	0.0000	0											
0.0000	-15.0000													
5.4479	-12.0000													
10.0000	-9.0000													
12.4896	-6.0000													
13.6250	-3.0000													
14.7083	0.0000													
6	58.2000	0.0000	0											
0.0000	-15.0000													
7.9792	-12.0000													
14.4375	-9.0000													
15.6146	-6.0000													
16.6875	-3.0000													
17.5417	0.0000													
6	48.5000	0.0000	0											
0.0000	-15.0000													
11.0729	-12.0000													
17.0000	-9.0000													
17.9479	-6.0000													
19.1667	-3.0000													
19.5625	0.0000													
6	38.8000	0.0000	0											

0.0000 -15.0000  
14.4896 -12.0000  
18.6250 -9.0000  
19.5313 -6.0000  
20.6250 -3.0000  
20.8750 0.0000  
6 19.4000 0.0000 0  
0.0000 -15.0000  
19.0938 -12.0000  
19.9375 -9.0000  
20.6354 -6.0000  
21.5000 -3.0000  
21.5000 0.0000  
6 0.0000 0.0000 0  
0.0000 -15.0000  
19.5833 -12.0000  
20.0625 -9.0000  
20.8229 -6.0000  
21.5000 -3.0000  
21.5000 0.0000  
6 -19.4000 0.0000 0  
19.5833 -15.0000  
20.1875 -12.0000  
20.8229 -9.0000  
21.5000 -6.0000  
21.5000 -3.0000  
21.5000 0.0000  
6 -38.8000 0.0000 0  
0.0000 -15.0000  
19.1354 -12.0000  
20.1250 -9.0000  
20.7500 -6.0000  
21.5000 -3.0000  
21.5000 0.0000  
6 -58.2000 0.0000 0  
0.0000 -11.6250  
19.1250 -9.0000  
19.6250 -7.5000  
20.1146 -6.0000  
20.5000 -3.0000  
21.5000 0.0000  
6 -67.9000 0.0000 0  
0.0000 -9.2500  
3.1250 -9.0000  
13.7500 -7.5000  
19.1042 -6.0000

19.9375 -3.0000  
21.4792 0.0000  
6 -77.6000 0.0000 0  
0.0000 -6.8750  
8.1667 -6.0000  
18.2500 -4.5000  
19.2500 -3.0000  
20.3750 -1.5000  
21.3750 0.0000  
6 -87.3000 0.0000 0  
0.0000 -4.7500  
3.0000 -4.6250  
6.0000 -4.2500  
17.2500 -3.0000  
18.8750 -1.5000  
20.6250 0.0000  
6 -97.0000 0.0000 0  
0.0000 -3.0000  
6.0000 -2.7500  
12.0000 -2.5000  
15.0000 -2.3750  
18.0000 -0.6250  
18.9792 0.0000  
1 -103.8759 0.0000 0  
0.0000 -2.0000  
5.2800 0.0000  
9999.0000 0.0000 0.000  
1.0000 0.2000 2.0000 0.1000 13.5025 13.5025 0.0000  
0.0000 180.0000 22.5000  
1.9000  
0.0



**APPENDIX B. BODY PLANS FOR T-AGOS CLASS 4 SHIP.**





## APPENDIX C. SAMPLE DATA AND OUTPUT FILE.

```
% Sets up required data sets for sea state, roll angle, and angle on ship
% Speed = 0-12 kt., Sea State = 1:8. 150x1 bilge keel
clear
```

```
th1=[0.0 22.5 45.0 67.5 90.0 112.5 135.0 157.5 180.0];
ss=[1 2 3 4 5 6 7 8];
speed=[0 2 4 6 8 10 12];
w=[0.0000,0.1190,0.2590,0.3350,0.1930,0.2490,0.2340,0.1390,0.0000;
0.0000,0.8550,1.4100,1.3900,0.8300,1.1400,1.0700,0.7080,0.0000;
0.0000,1.5700,2.3600,2.2400,1.5200,1.9400,1.9100,1.2900,0.0000;
0.0000,2.2900,3.2400,3.0500,2.3100,2.7500,2.7700,1.9600,0.0000;
0.0000,3.7500,4.9600,4.7500,4.0600,4.5000,4.5600,3.4200,0.0000;
0.0000,4.5800,6.0000,5.8200,5.1800,5.5700,5.5900,4.2600,0.0000;
0.0000,5.2600,6.8700,6.7600,6.2800,6.6100,6.5100,4.9200,0.0000;
0.0000,5.4400,7.2000,7.1700,6.7300,7.0300,6.8500,5.1400,0.0000;
0.0000,0.1760,0.3400,0.3730,0.1900,0.2220,0.1790,0.0991,0.0000;
0.0000,1.1700,1.7200,1.5000,0.8200,1.0300,0.8610,0.5190,0.0000;
0.0000,2.0000,2.7400,2.3700,1.5000,1.7600,1.5700,0.9640,0.0000;
0.0000,2.7400,3.6000,3.1900,2.2800,2.5500,2.3800,1.5600,0.0000;
0.0000,4.1000,5.2000,4.8100,4.0400,4.3400,4.2300,3.0800,0.0000;
0.0000,4.8200,6.1200,5.8200,5.1300,5.5000,5.3900,4.0000,0.0000;
0.0000,5.3400,6.9400,6.7000,6.2300,6.5400,6.4100,4.7800,0.0000;
0.0000,5.5300,7.2400,7.0800,6.6800,7.0300,6.8100,5.0400,0.0000;
0.0000,0.2900,0.4660,0.4180,0.1860,0.2000,0.1420,0.0740,0.0000;
0.0000,1.6500,2.1000,1.6000,0.7990,0.9320,0.7070,0.3970,0.0000;
0.0000,2.5600,3.1500,2.4800,1.4400,1.5800,1.3000,0.7390,0.0000;
0.0000,3.2700,3.9900,3.2500,2.1900,2.3100,2.0100,1.2300,0.0000;
0.0000,4.4400,5.4700,4.8100,3.9200,4.1000,3.8400,2.6900,0.0000;
0.0000,5.0300,6.3000,5.7600,5.0600,5.3100,5.0800,3.7100,0.0000;
0.0000,5.4800,6.9700,6.6000,6.1100,6.4800,6.2200,4.5600,0.0000;
0.0000,5.6700,7.2300,6.9600,6.5700,6.9600,6.6600,4.8600,0.0000;
0.0000,0.5900,0.7010,0.4760,0.1840,0.1810,0.1150,0.0572,0.0000;
0.0000,2.3800,2.6000,1.7200,0.7860,0.8600,0.6050,0.3190,0.0000;
0.0000,3.2100,4.5700,2.5500,1.3700,1.4400,1.1000,0.5940,0.0000;
0.0000,3.8100,4.3000,3.2500,2.0300,2.0800,1.7000,0.9630,0.0000;
0.0000,4.7500,5.6300,4.6600,3.6400,3.7700,3.3800,2.2300,0.0000;
0.0000,5.2400,6.3400,5.5300,4.7700,5.0400,4.7000,3.3000,0.0000;
0.0000,5.6200,7.0000,6.4000,5.8800,6.2600,5.9300,4.2500,0.0000;
0.0000,5.7500,7.2300,6.7500,6.3600,6.7900,6.4200,4.6100,0.0000;
0.0000,1.5500,1.2400,0.5460,0.1810,0.1650,0.0959,0.0455,0.0000;
0.0000,3.5700,3.4500,1.9100,0.7850,0.8000,0.5270,0.2640,0.0000;
0.0000,4.2700,4.3500,2.7400,1.3600,1.3500,0.9770,0.5000,0.0000;
0.0000,4.6900,4.9800,3.4000,1.9900,1.9600,1.5200,0.8180,0.0000;
```

```

0.0000,5.4300,6.0700,4.6800,3.5200,3.5700,3.1200,1.9700,0.0000;
0.0000,5.7700,6.7000,5.4700,4.6100,4.8200,5.6200,3.0200,0.0000;
0.0000,6.0700,7.2300,6.2400,5.7300,6.1400,5.7400,4.0100,0.0000;
0.0000,6.1700,7.4400,6.5700,6.2100,6.6700,6.2800,4.3900,0.0000;
0.0000,0.9200,2.5200,0.6370,0.1780,0.1500,0.0811,0.0372,0.0000;
0.0000,3.1600,4.7300,2.1400,0.7810,0.7440,0.4640,0.2230,0.0000;
0.0000,3.9800,5.4900,2.9900,1.3700,1.2700,0.8690,0.4280,0.0000;
0.0000,4.4900,6.0100,3.6600,2.0000,1.8700,1.3700,0.7070,0.0000;
0.0000,5.2800,6.9400,4.8600,3.5300,3.4900,2.9500,1.8100,0.0000;
0.0000,5.6700,7.4400,5.5700,4.6000,4.7700,4.2800,2.8700,0.0000;
0.0000,5.9700,7.8600,6.2800,5.7100,6.1200,5.6500,3.9200,0.0000;
0.0000,6.0700,7.9800,6.6000,6.2100,6.6700,6.2300,4.3300,0.0000;
0.0000,0.5980,2.3000,0.7630,0.1750,0.1380,0.0698,0.0310,0.0000;
0.0000,2.0400,5.2400,2.4300,0.7770,0.6950,0.4140,0.1930,0.0000;
0.0000,2.7200,6.1000,3.2900,1.3600,1.1900,0.7790,0.3720,0.0000;
0.0000,3.2100,6.6900,3.9200,2.0000,1.7700,1.2400,0.6170,0.0000;
0.0000,4.0400,7.5300,5.0600,3.5400,3.4000,2.7800,1.6600,0.0000;
0.0000,4.4900,8.0000,5.7700,4.6100,4.7200,4.1700,2.7500,0.0000;
0.0000,4.8400,8.3900,6.4400,5.7000,6.1200,5.6000,3.8600,0.0000;
0.0000,4.9600,8.5500,6.7500,6.2000,6.6900,6.2100,4.2900,0.0000];

```

```

% Utilizes a spline function to smooth data

for j= 1:7
    ctr=1;
    en=(j-1)*8 + 1;
    beg=en+7;
    for i=beg:-1:en
        t=0:180;
        w1(i,:)=spline(th1,w(i,:),t);
        w1p(ctr,:)=w1(i,:);
    ctr=ctr+1;
    end

    figure(j)
    plot(t,w1p(:, :))
    xlabel('Wave Angle (degrees - 150x1 bilge keel)')
    ylabel('Roll Angle (degrees)')
    s=speed(j);
    title(['Roll angle vs. wave angle (',int2str(s),' kts., sea states (ss) 1 to
8)'])
    legend('ss8','ss7','ss6','ss5','ss4','ss3','ss2','ss1',-1)
end

```

```

% Calculates maximum roll angle (2,4,6 degrees) for angle on ship.
ctr1=8;
ctr2=1;
for j1=1:7
    beg=(j1-1)*8 + 1;
    en=beg+7;
    ctr=1;
    for k=beg:en
        w1a(ctr,:)=w1(k,:);
        ctr=ctr+1;
    end

ra2=8.0*ones(1,181);
ra4=8.0*ones(1,181);
ra6=8.0*ones(1,181);
[r1,c1]=size(w1a);
ssn=1.00:0.01:8.00;
ssnc=size(ssn,2);

for i=1:c1
    wn=spline(ss,w1a(:,i),ssn);
    if wn(1,1) > 2.0
        ra2(i)=0.0;
    end
    if wn(1,1) > 4.0
        ra4(i)=0.0;
    end
    if wn(1,1) > 6.0
        ra6(i)=0.0;
    end

for j=1:(ssnc-1)

    if wn(1,j) <= 2.0
        k=j+1;
        if wn(1,k) > 2.0
            ra2(i)=ssn(j);
        end
    end

    if wn(1,j) <= 4.0
        k=j+1;
        if wn(1,k) > 4.0
            ra4(i)=ssn(j);
        end
    end

```

```

    end

if wn(1,j) <= 6.0
    k=j+1;
    if wn(1,k) > 6.0
        ra6(i)=ssn(j);
    end
end
end
end

```

% Sets up roll angle and theta matrices for plotting

```

for i=1:181
    z=i+180;
    th3(i)=t(i)*pi/180;
    th3(z)=t(i)*pi/180 + pi;
    j=182-i;
    ra2(z)=ra2(j);
    ra4(z)=ra4(j);
    ra6(z)=ra6(j);
end

```

% Prints out polar plot for sea state limits for roll angles of 2,4, and % 6 degrees for each speed.

```

figure(ctr1)
polar(th3,ra6,'r')
hold on
polar(th3,ra4,'b')
polar(th3,ra2,'g')
legend('g','2 degrees','b','4 degrees','r','6 degrees',-1)
xlabel('150x1 bilge keel')
hold off
s2 = speed(j1);
title(['Maximum sea state vs. wave angle (for ',int2str(s2),') kt. and 2,4,6
degree roll angle']])
pra2(ctr2,:)=ra2(1,:);
pra4(ctr2,:)=ra4(1,:);
pra6(ctr2,:)=ra6(1,:);
ctr1=ctr1+1;
ctr2=ctr2+1;
end

```

%Prints out polar plots for sea state limits for all speeds for 2,4, and

```

%6 degrees roll angles.
figure(15)
polar(th3,pra2(1,:),'y')
legend('0 kts',-1)
hold on
polar(th3,pra2(2,:),'m')
polar(th3,pra2(3,:),'c')
polar(th3,pra2(4,:),'r')
polar(th3,pra2(5,:),'g')
polar(th3,pra2(6,:),'b')
polar(th3,pra2(7,:),'w')
xlabel('150x1 bilge keel')
title('Maximum sea state vs. wave angle (for all speeds and 2 degree roll
angle)')
legend('y','0 kts','m','2 kts','c','4 kts','b','10 kts','w','12 kts',-1)
hold off

figure(16)
polar(th3,pra4(1,:),'y')
hold on
polar(th3,pra4(2,:),'m')
polar(th3,pra4(3,:),'c')
polar(th3,pra4(4,:),'r')
polar(th3,pra4(5,:),'g')
polar(th3,pra4(6,:),'b')
polar(th3,pra4(7,:),'w')
xlabel('150x1 bilge keel')
title('Maximum sea state vs. wave angle (for all speeds and 4 degree roll
angle)')
legend('y','0 kts','m','2 kts','c','4 kts','b','10 kts','w','12 kts',-1)
hold off

figure(17)
polar(th3,pra6(1,:),'y')
hold on
polar(th3,pra6(2,:),'m')
polar(th3,pra6(3,:),'c')
polar(th3,pra6(4,:),'r')
polar(th3,pra6(5,:),'g')
polar(th3,pra6(6,:),'b')
polar(th3,pra6(7,:),'w')
hold off
xlabel('150x1 bilge keel')
title('Maximum sea state vs. wave angle (for all speeds and 6 degree roll
angle)')
legend('y','0 kts','m','2 kts','c','4 kts','b','10 kts','w','12 kts',-1)

```

```

figure(1)
print -depsc2 g150x10.eps
figure(2)
print -depsc2 g150x12.eps
figure(3)
print -depsc2 g150x14.eps
figure(4)
print -depsc2 g150x16.eps
figure(5)
print -depsc2 g150x18.eps
figure(6)
print -depsc2 g150x110.eps
figure(7)
print -depsc2 g150x112.eps
figure(8)
print -depsc2 p150x10.eps
figure(9)
print -depsc2 p150x12.eps
figure(10)
print -depsc2 p150x14.eps
figure(11)
print -depsc2 p150x16.eps
figure(12)
print -depsc2 p150x18.eps
figure(13)
print -depsc2 p150x110.eps
figure(14)
print -depsc2 p150x112.eps
figure(15)
print -depsc2 p150x12d.eps
figure(16)
print -depsc2 p150x14d.eps
figure(17)
print -depsc2 p150x16d.eps

% Calculates areas under 2,4, and 6 degree curves to find operability
index
for i=1:7
    a15012(i)=trapz(th3,pra2(i,:));
    a15014(i)=trapz(th3,pra4(i,:));
    a15016(i)=trapz(th3,pra6(i,:));
end
diary on
a15012

```

a15014  
a15016  
diary off



## APPENDIX D. OUTPUT FILE FOR OPERABILITY INDICES.

% Operability index for no and all bilge keel sizes

sp=[0 2 4 6 8 10 12];

```
oi=[20.5352 19.6437 20.9513 21.8156 18.7591 22.2139
23.1490;
27.5689 25.4916 26.3032 27.0467 24.5390 27.0156 28.5117;
30.2916 28.4353 29.7059 30.6955 28.4974 30.8023 32.1364;
40.6990 40.6389 40.4951 40.1558 39.2916 36.7968 35.2270;
50.2655 50.2655 50.2655 50.2655 50.2655 50.2655 50.2655;
50.2655 50.2655 50.2655 50.2655 50.2655 50.2655 50.2655;
31.5754 31.4809 31.0794 30.4644 29.0074 28.0754 28.4607;
50.1601 50.1964 49.9981 49.5953 49.2371 47.6217 46.2013;
50.2655 50.2655 50.2655 50.2655 50.2655 50.2655 50.2655;
23.6220 23.6932 23.5707 23.6384 22.6258 22.2212 24.0342;
33.8953 33.9282 34.0430 33.5065 32.3755 32.3211 33.3536;
43.4954 43.5624 43.7010 44.2738 43.9998 43.0580 42.8258;
33.1574 33.1825 33.0098 32.4087 30.8072 29.5798 29.5969;
50.2655 50.2655 50.2655 50.2655 50.2655 49.3792 47.5442;
50.2655 50.2655 50.2655 50.2655 50.2655 50.2655 50.2655;
27.0449 26.8404 26.5161 26.0630 26.1045 24.8517 25.7132;
41.0418 40.9971 40.9294 41.1273 41.0348 38.2164 38.5906;
50.2655 50.2655 50.2655 50.2655 50.2655 50.2655 49.1335;
22.0652 22.1496 22.1688 22.0700 21.2421 21.4560 23.5047;
30.9436 30.9119 30.7803 30.6469 29.1149 29.6535 31.1143;
36.6973 36.9689 37.3480 38.3693 37.8269 37.2617 37.9979;
28.3462 28.0363 27.6600 27.1524 26.0138 25.6165 26.4812;
43.5711 43.6137 43.4905 43.4775 42.7571 41.5179 40.6086;
50.2655 50.2655 50.2655 50.2655 50.2655 50.2655 50.1873;
24.0074 24.0688 23.9180 23.6660 22.7242 22.4861 24.2154;
34.6294 34.7334 34.8465 35.1848 33.7725 33.0551 33.9994;
45.0302 45.0246 45.2023 45.7350 45.5974 44.6895 44.3698;
21.3010 21.2152 21.3695 21.3614 20.2741 21.2836 23.1232;
29.3208 28.9641 28.7246 28.6705 27.1758 28.4457 30.0060;
33.6042 33.5519 33.9582 34.9195 33.6370 33.9735 35.0874];
```

% changes operability index to % for no bilge keel

max=50.2665;

for i=1:3

pooi(i,:)=oi(i,:)/max;

```

end

% compares operability index of no bilge keel to different bilge keels

for i=4:3:30
    l=i+1;
    m=i+2;
for j=1:7
    pooi(i,j)=oi(i,j)./oi(1,j);
    pooi(l,j)=oi(l,j)./oi(2,j);
    pooi(m,j)=oi(m,j)./oi(3,j);
end
end

```

%Printing out results

```

figure(1)
plot(sp,pooi(1,:),sp,pooi(2,:),sp,pooi(3,:))
xlabel('Speed (kts)')
ylabel('Operability Index')
title('Operability Index for no bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oinbk.eps
figure(2)
plot(sp,pooi(4,:),sp,pooi(5,:),sp,pooi(6,:))
xlabel('Speed (kts)')
ylabel('Operability Index comparison')
title('Operability Index for 150x3 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi150x3.eps
figure(3)
plot(sp,pooi(7,:),sp,pooi(8,:),sp,pooi(9,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 150x2 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi150x2.eps
figure(4)
plot(sp,pooi(10,:),sp,pooi(11,:),sp,pooi(12,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 150x1 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi150x1.eps
figure(5)

```

```

plot(sp,pooi(13,:),sp,pooi(14,:),sp,pooi(15,:))
xlabel('Speed (kts)')
ylabel('Operability Index')
title('Operability Index for 75x3 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi75x3.eps
figure(6)
plot(sp,pooi(16,:),sp,pooi(17,:),sp,pooi(18,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 75x2 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi75x2.eps
figure(7)
plot(sp,pooi(19,:),sp,pooi(20,:),sp,pooi(21,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 75x1 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi75x1.eps
figure(8)
plot(sp,pooi(22,:),sp,pooi(23,:),sp,pooi(24,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 37.5x3 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi375x3.eps
figure(9)
plot(sp,pooi(25,:),sp,pooi(26,:),sp,pooi(27,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 37.5x2 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi375x2.eps
figure(10)
plot(sp,pooi(28,:),sp,pooi(29,:),sp,pooi(30,:))
xlabel('Speed (kts)')
ylabel('Operability Index Comparison')
title('Operability Index for 37.5x1 bilge keel and 2,4, and 6 deg roll angle')
legend('2 deg','4 deg','6 deg',-1)
print -depsc2 oi375x1.eps

```



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